Statistical study of warps in a sample of spiral and lenticular galaxies

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Abstract A sample of edge-on (or nearly edge-on) spiral and lenticular galaxies is selected to study the warp phenomenon in their disks. This sample contains 36 disk galaxies selected from Watanabe’s catalogue (Watanabe, 1983). We investigate the existence of physical relations between photometric and spectroscopic parameters and the warp degree of galaxies.

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1. Introduction

Since the first observations of warp in our Galaxy and in other galaxies (Burke, 1957; Kerr, 1957 and Sancisi, 1976), the origin and persistence of galactic warps have been a matter of research for decades. The disks in most disk galaxies are not flat and their outer parts often show warping of the material away from the galactic plane (Sanchez-Saavedra et al., 1990; Reshetnikov and Combes, 1998; Ann and Park, 2006). Warps are mostly seen in the 21 cm neutral hydrogen line (Sancisi, 1976; Bosma, 1978; Briggs, 1990; Bottema, 1995; Garcia-Ruiz et al., 2002) and in the optical bands (Sanchez-Saavedra et al., 1990; Reshetnikov and Combes, 1999; Drimmel et al., 2000; Reshetnikov et al., 2002). Garcia-Ruiz et al. (2002) analyzed HI observations and found that all edge-on galaxies that have an extended HI disk (with respect to the optical component) are warped. Thus the warps are a common phenomenon and hence must be either continuously being excited or they are stable over long periods of time.

Most of the studies of the warps were a statistical, N-body simulations and theoretical models to explain warp formation (Revaz and Pfenniger, 2001, 2004; Sanchez-Salcedo, 2006; Lodato and Pringle, 2007; Saha et al., 2009; Lodato and Price, 2010; Roskar et al., 2010; Facchini et al., 2013; Sadoun et al., 2014; Haan and Braun, 2014; de Blok et al., 2014; Kim et al., 2014; Kaufman et al., 2015).

Several mechanisms that trigger and maintain warps have been proposed, including tidal interactions between galaxies, inter-galactic magnetic fields, cosmic infall, disk-halo interaction and matter accretion (Battaner et al., 1990; Binney, 1992; Battaner and Jimenez-Vicente, 1998; Jiang and Binney, 1999; Debattista and Sellwood, 1999; Revaz and Pfenniger, 2001; Semelin and Combes, 2005; Shen and Sellwood, 2006; Weinberg and Blitz, 2006; Dubinski and Chakrabarty, 2009).

One of the proposed qualitative studies of the warp phenomena and its relation with physical properties of galaxies is the warp angle introduced by Sanchez-Saavedra et al.
In a study of Reshetnikov and Combes (1999), they did not find a correlation between the warp angle and the blue absolute magnitude for some warped spiral galaxies. Radburn-Smith et al. (2014) studied the gaseous H I warp of NGC 4565 and they found a clear correlation of young stars (<600 Myr) with the warp, but no coincident old stars (>1 Gyr), which places an upper limit on the age of the structure.

In this work, we study the possible correlations between the warp degree (W) and different photometric and spectroscopic parameters of the present sample of disk galaxies (such as the major diameter, axis ratio, mean surface brightness, absolute magnitude, B-V color, central velocity dispersion and rotation velocity). In this study we used a cosmological model with H0 = 70 km s\(^{-1}\) Mpc\(^{-1}\), \(\Omega_m = 0.3\) and \(\Omega_{\Lambda} = 0.7\) for all the calculated numerical values. The paper is laid out as follows. In Section 2 the criterion describing the warp degree (W) is outlined. In Section 3, the sample of galaxies is described. The results and discussion are presented in Section 4 while the conclusions are summarized in Section 5.

2. The warp criterion

One of the proposed criteria used to describe the presence of a warp in a galaxy is the warp angle \(\Psi\) defined as the angle between the major axis and the line from the galactic center to the highest observed departure of the plane of symmetry is the warp angle (Sanchez-Savedra et al. 1990, 2003).

Table 1  General data of the galaxies in the present sample. Column 1 lists the galaxy number as recorded in Watanabe's catalogue (Watanabe, 1983). Column 2 is the NGC’s ID for each galaxy. Column 3 and 4 list the morphological type and type index as recorded in HYPERLEDA database. Column 5 is the total V magnitude (Watanabe, 1983), while column 6 presents the inclination of the galaxy (Watanabe, 1983). Column 2 is the NGC's ID for each galaxy. Column 3 and 4 list the morphological type and type index as recorded.
A new criterion for detecting (and measuring) the degree of warp was suggested by Gamaleldin (1992, 1995). The suggested warp criterion is the warp degree \( W \), introduced by Gamaleldin (1992, 1995):

\[
W = \left( \frac{A_w}{A_i} \right) \times 100
\]  

(1)

HW (high warp) if \( W \geq 10\% \)
MW (medium warp) if \( 10\% > W \geq 5\% \)
LW (low warp) if \( 5\% > W \geq 2\% \)
NW (no warp) if \( W < 2\% \)

The warped area \( A_w \) is defined as the difference between the area of the fitted ellipse \( A_e \) and the area of the isophote \( A_i \):

\[
A_w = A_i - A_e
\]  

(2)

The best ellipse of the isophote was calculated by applying the least square solution. The warp degree \( W \) is defined as the percentage of the warped area, \( A_w \), to the isophotal area, \( A_i \).

The disadvantage of the warp angle \( \Psi \) (Sanchez-Savedra et al., 1990, 2003) is its dependence on the eye estimation, and the determination of the direction of the major axis of the rotating isophote is difficult, especially in the presence of the position angle variation (Liller, 1960; Gamaleldin and Issa, 1983). The main advantage of the proposed criteria is that it is independent of the eye estimation.

The procedure works as follows: the outer isophote at 24.5 V-mag of each galaxy in the sample is fitted to an ellipse where the area of the isophote, \( A_i \), and the area of the ellipse, \( A_e \) are obtained.

Figure 1  The contour map (left) and the image (right) of the S0-a galaxy NGC 4488 with \( W = 16\% \). North is at top (Watanabe, 1983).

Figure 2  Histogram of morphological type index, \( T \), of the studied sample.

Figure 3  Histogram of the warp degree (\( W \)) of the studied sample.
Table 2  The mean of some of the galaxy parameters for the whole sample and the $W \geq 10$ sample and their correlations with warp degree parameter, $W$.

| Parameter | The whole sample | Corr | The $W \geq 10$ sample | Corr |
|-----------|------------------|------|------------------------|------|
| $D$       | 9.553 ± 5.079    | 0.165| 9.717 ± 4.682          | 0.022|
| Axis ratio| 0.299 ± 0.092    | -0.133| 0.291 ± 0.08           | 0.152|
| SB        | 23.346 ± 0.465   | 0.368| 23.522 ± 0.443         | 0.029|
| $M_v$     | -19.311 ± 1.599  | -0.17| -19.28 ± 1.34          | 0.128|
| B-V       | 0.7 ± 0.154      | -0.373| 0.625 ± 0.175          | 0.175|
| $V_{\text{dis}}$ | 110.278 ± 43.019 | -0.319| 95.682 ± 44.739        | -0.301|
| $V_{\text{rot}}$ | 142.689 ± 45.355 | 0.048| 183.143 ± 44.981       | 0.263|

Figure 4  Plot of major diameter at 24.5 V-mag (D24.5) in kpc versus warp degree ($W$): (a) for all galaxies in the sample and (b) for galaxies with $W \geq 10\%$.

Figure 5  Plot of axis ratio ($b/a$) versus warp degree ($W$) of the studied sample: (a) for all galaxies and (b) for galaxies with $W \geq 10\%$. 
3. The sample

We preferred to take our data from one source for homogeneity of observations and reductions. We took our sample from Watanabe’s catalogue (Watanabe, 1983) which represents digital surface photometry of 261 galaxies that were obtained in the V band with the 105 cm Schmidt telescope at the Kiso Observatory, Japan.

We visually inspected the Watanabe’s catalogue and obtained 36 nearly-edge on ($61.1–90^\circ$) lenticular and spiral galaxies with a clear sign of warp (see Table 1, Figs. 1 and 2). The studied sample contains the V-magnitude between 13.75 and 9.64 magnitudes respectively. Their inclinations were checked from the LEDA database. Fig. 1 shows, as an example, the contour maps and the image of NGC 4488 whose warp degree is $W = 16\%$. It is clear that the warp is more obvious in the outer isophotes than in the inner isophotes.

4. Results and discussion

The isophote at 24.5 V-mag of each galaxy in the sample is fitted to an ellipse to get the warp degree, $W$ of the outer isophote, as described in Section 2. The maximum value of the warp degree is 16% while the minimum is 3%. In the sample, 20 galaxies are found to have $W \geq 10\%$ while the rest have $W < 10\%$. The histogram of the warp degree, $W$, is shown in Fig. 3 where slightly more than half of the studied sample have $W$ degree greater than or equal to 10%.
Fig. 2 represents a histogram for the morphological type of our studied sample of galaxies where the type S0-a ($T = 0$) is the dominant.

The correlations between the galaxy’s parameters in the sample and their warp degrees are listed in Table 2. The correlation is, in general, poor for both the whole sample and for the $W > 10\%$ sample.

The dependence of the warp degree on the major diameter at the 24.5 V-mag isophote of the studied sample is illustrated in Fig. 4. The whole sample and the $W > 10\%$ sample show a poor correlation (Fig. 4a and b and Table 2).

Fig. 5 shows the dependence of the warp degree on the axis ratio where the whole sample and the $W > 10\%$ sample show a poor correlation (Fig. 5a and b and Table 2).

In Fig. 6 the mean surface brightness (SB) within the 26th-mag isophote is plotted against the warp degree $W$ where the whole sample and the $W > 10\%$ sample show a poor correlation (Fig. 6a and b and Table 2).

The dependence of the warp degree, $W$, on the corrected color index, B-V, is shown in Fig. 8. The whole sample and the $W > 10\%$ sample show a poor correlation (Fig. 8a and b and Table 2).

For the dynamical parameter, the central velocity dispersion, $V_{\text{dis}}$, the correlation between $W$ and $V_{\text{dis}}$ is very poor (Fig. 9a and b and Table 2).
In Fig. 10 the apparent maximum rotation velocity of the gas, $V_{\text{rot}}$, is plotted against $W$ of the studied sample. The whole sample and the $W \geq 10\%$ sample show a poor correlation (Fig. 10a and b and Table 2).

5. Conclusions

We used the warp degree $W$ to measure and study the warp in a sample of 36 disk galaxies. The values of the highest and lowest warp degrees for the studied sample are 16% and 3% respectively, where 20 galaxies are found to have warp degree $W \geq 10$ and 16 galaxies have $W < 10$. The correlations between $W$ and some photometric and dynamic parameters for each galaxy in the sample are also studied (Table 2). All correlations are found to be poor which may be attributed to the relatively small number of the galaxies in the sample. The calculated correlation coefficients of the studied sample for $W \geq 10$ are positively correlated except for the velocity dispersion $V_{\text{dis}}$ (corr = -0.3). These points will be under investigation in the future work.

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Figure 10 Plot of apparent maximum rotation velocity of gas ($V_{\text{rot}}$) versus warp degree ($W$) of the studied sample: (a) for all galaxies and (b) for galaxies with $W \geq 10\%$.
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