Near-Infrared and Optical Observations of Galactic Warps

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Abstract Warps in galactic disks have been studied extensively in HI and in the optical, but very rarely in the near-infrared (NIR) bands that trace the older stellar populations. We have obtained observations of 20 edge-on galaxies in the NIR and in several optical bands. We compare the properties of the galactic warps as a function of wavelength in our sample galaxies. We calculate a warp curve for each galaxy, from which we obtain the characteristic warp parameters. A systematic analysis of these parameters may help us to constrain the different mechanisms that have been proposed for the development and maintainace of galactic warps. Our results show that 13 of the 20 galaxies are warped, with the warp being more pronounced in the optical than at NIR wavelengths. The transition between the unperturbed inner disk and the outer warped region is rather abrupt. Our data are compatible with lenticulars showing very small or no warps.

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1 Sample, Observations and reduction

We selected 20 candidates from a statistically complete diameter limited subsample of edge-on disk ($i > 87°$) isolated galaxies with optical diameters (at a surface brightness level of μ_B = 25 mag/arcsec^2, in the blue band) larger than 2.2' and morphological type range from S0 to Sd. Our sample was selected by de Grijs (1997, 1998) from the Surface Photometry Catalogue of the ESO-Uppsala Galaxies (ESO-LV, Lauberts & Valentijn 1989). The sample was observed in the optical (B, V, I filters) with the Danish and the Dutch Telescopes of the ESO at La Silla, and in NIR wavelengths (K_{short} filter) with the 1.5m Telescope of the CTIO at Cerro Tololo. We have obtained a precise value of the surface brightness in the most external part (fainter than 26 mag/arcsec^2 at the B band and 23 mag/arcsec^2 with the K_{short} filter.

2 Warp Curve

Images in each filter were aligned and scaled. Stars in the background were carefully masked. To determine the warp curve, the curve of the position of the maximum in intensity as a function of radius, we have fitted Gaussians to each column (minor axis). We only considered data with intensity greater than 3σ ($\sigma = \sqrt{\sigma_{\rm sys}^2 + \sigma_{\rm std}^2}$, where $\sigma_{\rm sys}$ is the systematic error due to background noise and $\sigma_{\rm std}$ is the standard deviation), and with a FWHM of the peak smaller than 100 pixels. An example of the results of our analysis is presented in Fig. 1. Only points with an estimate better than 0.5" are used in the warp curve.

2.1 Warp Parameters

It is convenient to give a geometric definition of the warp, useful e.g. for statistical studies. The warp curve is defined as the locus of points x_i, y_i off the deviation with respect to the symmetry plane, where y_i is the position of the center of the best fitting Gaussian at a given x_i. Let us define the warp parameter as is described in Jiménez-Vicente et al. (1997) and López-Corredoira et al. (2008), ω,

$$\omega = \frac{1}{L^3} \int_{-L/2}^{+L/2} xy d\mathrm{x} \qquad (1)$$

where L is the size of the whole edge-on galaxy, which is defined as the diameter at the isophotal level K_s = 22 mag/arcsec^2, 3σ above the sky background. One of the most important errors in estimating the warp parameter ω, arises from the imperfect determination of the position angle of the major axis, resulting in an error α in the PA. As $\alpha \neq 0$ we introduce the error

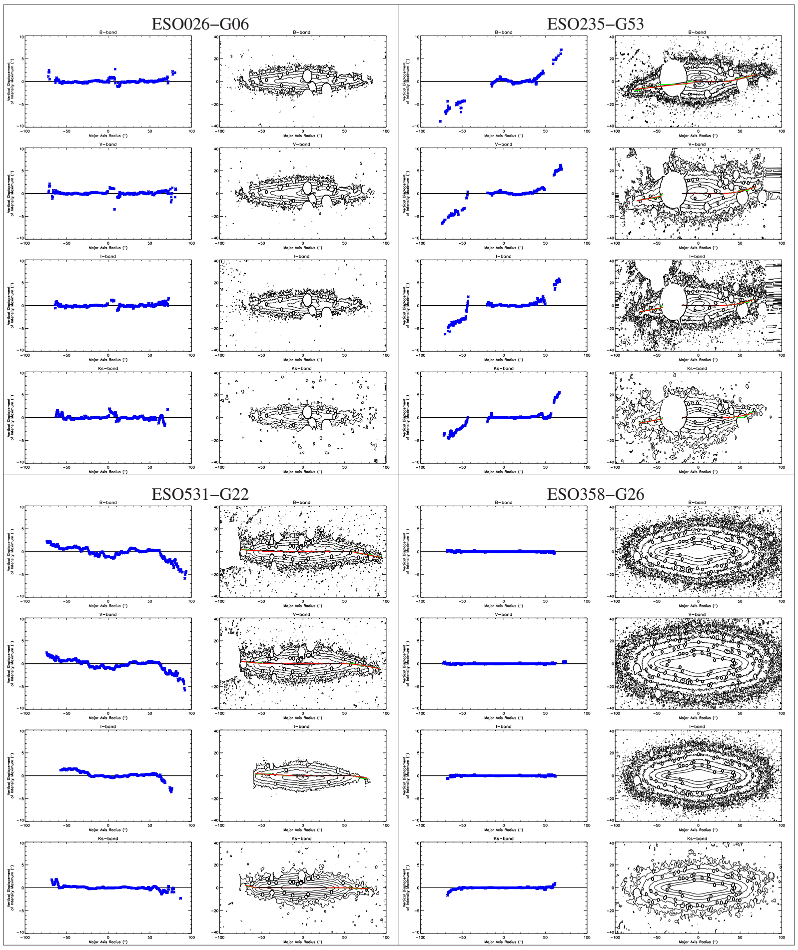

Fig. 1 Warp curves and contour map of 4 galaxies in the four analyzed filters. Left-up: ESO026-G06 as an example of unwarped galaxy. Right-up: ESO235-G53 as an example of galaxy with optical and NIR warp. Left-down: ESO531-G22 as an example of optical warp and NO NIR warp. Right-down: ESO358-G29 as an example of lenticular galaxy without warp.

$$\Delta\omega = \frac{1}{L^3}\int_{-\infty}^{\infty} x(\mathrm{x}\tan\alpha)\mathrm{dx} \approx \frac{1}{3\mathrm{L}^3}\mathrm{L}^3\alpha \approx \frac{\alpha}{3} \qquad (2)$$

As α was in general of about 0.05°, i.e. 9×10^{-4} radians, we estimate $\Delta\omega$ of the order of 3×10^{-4}. A large warp could have a value of 10×10^{-4} and a barely perceptible warp, 5×10^{-4}. The total error in estimating ω would be $\varepsilon_\omega = \sqrt{(\frac{\chi^2}{\mathrm{DOF}})^2 + (\Delta\omega)^2}$. For those galaxies showing an appreciable warped disk, we also fit some parameters for the warp curve. To do this we have used the function which is described in Jiménez-Vicente et al. (1997) to fit each side of the warp:

$$z = \begin{cases} 0 & |x| < |A| \\ C\left((x-A) - B\left(1 - e^{-\frac{|x-A|}{B}}\right)\right) & |x| \geq |A| \end{cases} \tag{3}$$

This function reproduces the shape of a warp, i. e., it is flat up to a point and then deviates from the symmetry plane until it reaches an asymptotic direction. The parameter A is the starting point of the warp. B is the characteristic length in which the warp reaches the asymptotic direction. A and B have dimensions of length. C is the (non-dimensional) value of the asymptotic slope.

3 Analysis

- We obtain that 13 out of 20 galaxies are warped, therefore 65% of disks. Given the difficulties of observing warps, this indicates that practically all spiral galaxies are warped.
- The comparison between the optical and NIR bands is difficult, due to inherent errors and because warps are not very large.
- We found no significant dependence of warp parameters on galaxy morphology, except for unwarped lenticular galaxies.
- We find a small tendency for NIR warps to have lower absolute values of the fitting parameter C (the asymptotic slope).

4 Conclusions

1. The warp is more pronounced in the optical than at NIR wavelengths.
2. Our data are compatible with lenticular galaxies showing very small or no warps.
3. The transition between the unperturbed inner disk and the outer warped region is rather abrupt.
4. This suggests that warps are long-lived and they were formed in the early galaxy. Then the mechanism responsible, whatever it was, is acting permanently.
5. The magnetic model is consistent with all these properties.

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