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A strong correlation between bar strength and global star forming activity in isolated barred galaxies

J.A.L. Aguerri

Instituto de Astrofísica de Canarias, 38200 La Laguna, Tenerife, Canary Islands, Spain (jalfonso@ll.iac.es)

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Abstract. I have studied the relation between the global star formation activity and the bar structure in a sample of isolated barred galaxies. The star formation activity was quantified via the ratio between the IRAS fluxes at 25 μm and 100 μm. Two parameters were chosen to define the bar structure: the strength of the bar and the relative projected bar length. The strength of the bar was defined by $\epsilon_b = 10(1 - b/a)$, where a and b are the projected semi-major and semi-minor bar axis. The relative bar length was defined as: $2L_b/D_{25}$, where L_b is one half of the projected total bar length and D_{25} is the diameter of the 25 mag arcsec^{-2} magnitude isophote in the B band. We found a strong correlation between the star formation activity and ϵ_b. The regression line is given by $log(I_{25}/I_{100}) = -1.81 + 0.093\epsilon_b$, with a correlation coefficient of 0.9. The link is not so evident between the relative projected bar length and the star formation activity. But, it is noted that there is enhanced star formation activity in galaxies with strong bars and small relative bar lengths, $0.1 < 2L_b/D_{25} < 0.22$.

Key words: galaxies: spiral – galaxies: stellar content – galaxies: statistics

1. Introduction

The star formation process in spiral galaxies is a complex phenomenon not yet fully understood. Since the pioneering work of Bertin Lindblad on the spiral structure in galaxies, many papers have been published on this topic (for a recent review see Kennicutt 1998). Several global properties of a galaxy can influence its star formation activity: the total mass (Gavazzi & Scodeggio 1996; Gavazzi et al. 1996), bars (see below), spiral arms (Elmegreen & Elmegreen 1986; McCall & Schmidt 1986) and environmental effects (Bushouse 1987; Kennicutt et al. 1987; Telesco et al. 1988; Liu & Kennicutt 1995). In this letter we concentrate on the relation between the bar structure and the global star formation.

Barred features are very common among galaxies; about a third of spiral galaxies show a strong bar, and another third have a weaker bar (see, e.g. Freeman 1996). Understanding the connection between the presence of a bar and other aspects of galaxy morphology and dynamics is one main challenges of current galactic astrophysics.

The presence of a bar (or similar non-axisymmetric structure) in the disc of a galaxy changes its dynamics dramatically, as evidenced by the deviations from circular motion in the velocity maps of barred galaxies. The isovelocity curves in the bar tend to align with the bar major axis. It is well known that non-axisymmetric structures are at least partly responsable for the feeding of gas to the nucleus (Arsenault 1989; Quillen et al. 1995). Numerical simulations have also shown that the direction of n on-circular motions induced by the presence of a bar, inside the bar corotation, are toward the center of the galaxy. Inside corotation, the dissipative gaseous component loses angular momentum to the stars and falls inward (Schwarz 1984, Wada & Habe 1992, Friedli & Benz 1993). However, the relationship of the bar and starburst or Seyfert activity in spiral galaxies is controversial (Hawarden et al. 1986, Ho et al. 1997).

Stellar bars perturb the gas in the whole galactic disk and they could thus affect the global star formation in spiral galaxies. Although the relation between the global star formation and the presence of a bar in galaxies has been investigated by many authors, the results are discrepant. Some studies claim that the star formation is enhanced in barred galaxies (Hawarden et al. 1986; Dressel 1988; Arsenault 1989; Huang et al. 1996; Martinet & Friedli 1997) while others suggest that barred galaxies have star formation levels similar to those of normal spirals (Pompea & Rieke 1990; Isobe & Feigelson 1992; Ryder & Dopita 1994; Tomita et al. 1996).

Martinet & Friedli (1997) found a weak relation between the star formation rate measured in the far-infrared (FIR) and the strength of the bar in a sample of isolated barred galaxies. In other words, stronger bars display more enhanced star formation. The aim of this work is to revise this relation, paying special attention to the selection criteria of the sample.

2. The sample of galaxies

As an initial sample I used all the barred galaxies studied by Martin (1995). This sample was supplemented by SB and SAB galaxies of Hubble types Sb to Sd taken from de Vaucouleurs et al. (1991). Only galaxies without uncertainties in their morphological classification were taken into account. As pointed out above, the aim is to see how the bar structure affects the star formation in a barred galaxy. In order to avoid galaxies which have enhanced star formation by other mechanisms (notably by interactions), we searched for companions to the galaxies presented by Martin (1995), and eliminated those with companions from the sample. This was performed with the help of the NASA/IPAC Extragalactic Database (NED).

According to our criteria, a galaxy has a companion if there is another one within a projected distance of 500 kpc, and the systemic velocity difference is less than 500 km s^{-1} (Marquez & Moles 1996). Using these criteria many of the galaxies presented by Martinet & Friedli (1997) are not isolated.

AGN and Seyfert galaxies have not been included in the sample. However, NGC 6951 presents a LINER nucleus. No galaxy of the sample is catalogued as starburst. Galaxies with evidence of recent mergers were also excluded from the final sample, since mergers could well change the strength of the bar and affect the star formation history of the galaxy (e.g. NGC 7479 Laine & Heller 1999). The final sample has 29 galaxies, of which 25 are late-type and 4 Sb type. Table 1 shows the final sample of isolated galaxies.

Table 1. The sample of galaxies used in this study

Galaxy[a]	Type[b]	I_{25}^{c}	I_{100}^{d}	$(b/a)^{e}$
NGC 10	SAB(rs)bc	0.2113	3.189	0.48
NGC 151	SB(r)bc	0.2549	5.576	0.53
NGC 578	SAB(rs)c	0.2477	11.69	0.87
NGC 1187	SB(r)c	1.433	24.06	0.43
NGC 1313	SB(s)d	3.49	92.00	0.63
NGC 1530	SB(rs)b	0.8402	21.92	0.51
NGC 1637	SAB(rs)c	1.043	14.46	0.40
NGC 1784	SB(r)c	0.2495	8.864	0.58
NGC 2935	(R)SAB(s)b	0.3915	11.13	0.59
NGC 3319	SB(rs)cd	0.2868	4.324	0.32
NGC 3344	(R)SAB(r)bc	0.4886	22.54	0.86
NGC 3359	SB(rs)c	0.59	16.76	0.48
NGC 3811	SB(r)cd	0.1733	5.497	0.55
NGC 3887	SB(r)bc	0.63	16.81	0.50
NGC 5000	SB(rs)bc	0.1271	2.385	0.31
NGC 5260	SB(s)c	0.1990	2.841	0.3
NGC 5334	SB(rs)c	0.2696	3.316	0.27
NGC 5584	SAB(rs)cd	0.2751	6.046	0.51
NGC 5645	SB(s)d	0.2097	4.52	0.48
NGC 5669	SAB(rs)cd	0.1216	5.193	0.77
NGC 5885	SAB(r)c	0.397	8.077	0.49
NGC 5888	SB(s)bc	0.0597	1.299	0.62
NGC 6691	SB(rs)bc	0.1606	4.171	0.59
NGC 6711	SBbc	0.2984	4.27	0.3
NGC 6907	SB(s)bc	1.343	29.57	0.43
NGC 6951	SAB(rs)bc	1.374	37.47	0.46
NGC 7046	SB(rs)cd	0.1364	2.119	0.44
NGC 7171	SB(rs)b	0.1338	3.330	0.56
NGC 7329	SB(r)b	0.0747	2.729	0.72

[a] NGC name of the galaxy;
[b] Galaxy type from de Vaucouleurs et al. (1991);
[c] IRAS 25 μm flux in Jy;
[d] IRAS 100 μm flux in Jy;
[e] ratio between the projected semi-minor and semi-major bar axes.

3. Star formation

There are several quantitative estimators of active star formation in spiral galaxies. Among others the Hα luminosity (Kennicutt 1989, 1998), UV emission (Smith & Cornett 1982; Donas et al. 1987,1995; Deharveng et al. 1994), FIR emission (see below) and radio continuum (Helou 1991). None of these estimators is unambiguous. The necessity to have a sample as large as possible with data both on bar morphology and star formation activity leads us to prefer FIR to other star formation estimators, such as Hα.

A significant fraction of the bolometric luminosity of a galaxy is absorbed by the interstellar dust and re-emitted in the thermal infrared at wavelengths between 10 and 300 μm. The FIR emission should thus be a sensitive tracer of the young stellar population and recent star formation. The IRAS survey provides FIR fluxes for a great number of galaxies from 10 μm to 100 μm. Several authors have used the ratios between IRAS fluxes as indicators of recent star formation in galaxies (Rowan-Robinson & Crawford, 1989; Puxley et al. 1988; Hawarden et al. 1986). However, Dultzin-Hacyan et al. (1990) argue that the ratio (I_{25}/I_{100}), where I_{25} and I_{100} are the IRAS fluxes at 25 μm and 100 μm, respectively is the best IRAS tracer of recent star formation. They suggest that the emission at 25 μm is due to hot thermal gas heated by OB associations and/or shocked dusty gas. Kennicutt (1983) and Keel (1983) observed a correlation between the global to central Hα flux ratio and $log(I_{25}/I_{100})$. This further suggests that information on star formation activity is contained in $log(I_{25}/I_{100})$. This ratio was chosen as a tracer of recent star formation in the present work. The IRAS fluxes were obtained from the NED database, and the values are given in columns III and IV of Table 1.

4. Results and discussion

There are several methods to compute the strength of the bar in a barred galaxy (Martin 1995; Rozas et al. 1998). We have taken the strength of the bar as parameterised by Martin (1995),

$$\epsilon_b = 10(1 - b/a), \quad (1)$$

where a and b are the projected semi-major and semi-minor axes of the bar, respectively. Perfect spherical bulges show $\epsilon_b = 0$ while strong bars show $\epsilon_b \approx 8$.

The values of a and b given by Martin (1995) were obtained by careful visual measurements from the atlas of Sandage & Bedke (1988). Chapelon et al. (1999) have estimated that the uncertainty of this method is about 20%. We have recalculated these values from the ellipticity of the isophotes at the end of the bar. These ellipticities have been obtained using the program ELLIPSE in IRAF. The images used were obtained from the NED database. These images are from the digitalized Schmidt survey plates, with a resolution of $1.7''$, which is adequate for

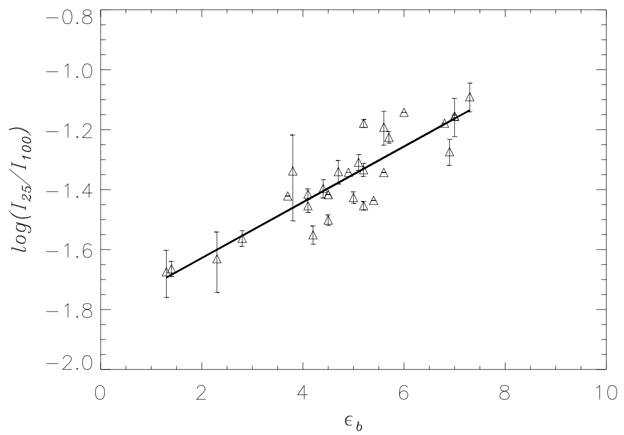

Fig. 1. Relation between the global star formation given by $log(I_{25}/I_{100})$ and the strength of the bar (ϵ_b). The thick line is the regression line. See text for details

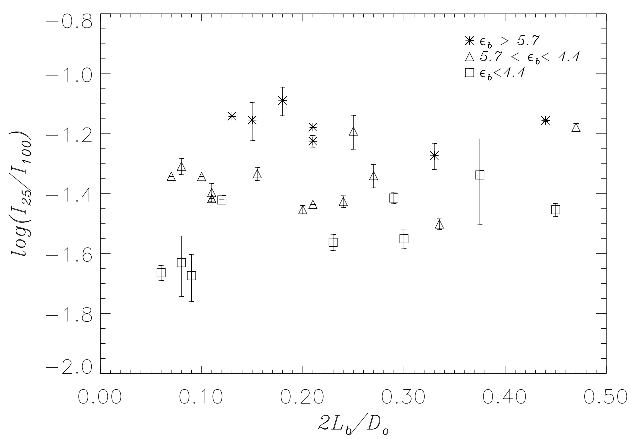

Fig. 2. Relation between the global star formation given by $log(I_{25}/I_{100})$ and the relative length of the bar ($2L_b/D_o$). See text for details

all the galaxies in my sample. These images were taken in the optical V band.

The end of the bar was defined by studying the ellipticity and position angle profiles obtained from the isophotal fitting. These profiles provide information on the different structural components of the galaxies. For example, in a spiral galaxy which only shows a bulge and a disk, the ellipticity of the isophotes is almost zero at the center and increases monotonically until it reaches a constant value which corresponds to the inclination of the disk. In a galaxy with a bar feature, the ellipticity grows from values of almost zero in the center to a local maximum at the end of the bar. The ellipticity then approaches a value corresponding to the inclination of the disk (Wozniak et al. 1995). The ellipticity of the isophotes at this maximum was taken as the b/a value for the bars in my sample of galaxies. In column V of Table 1 we list our projected values of b/a; some of these are different from those given by Martin (1995).

The presence of star formation and dust at the end of the bar affects the ellipticity of the isophotes in this region. This effect can be reduced by using near-infrared images which are less affected by dust and star formation events. Aguerri et al. (1998) published the ellipticity ($1 - a/b$) for 10 barred galaxies. It was observed that the ellipticity is a little greater in B than in I. This implies that by using optical images we are overestimating the strength of the bar. The maximum deviation in the ellipticity in the sample of Aguerri et al. (1998) was around 0.05. Therefore, the maximum amount of overestimation in the bar strength should be around 0.5. We have used V band images which are less affected by dust and star formation than B images. Therefore, our maximum uncertainty in the bar strength will be less than 0.5.

The relation between $log(I_{25}/I_{100})$ and the bar strength is shown in Fig. 1. Although we do not have a large number of galaxies, it is evident that the stronger the bar, the more enhanced is the star formation of the galaxy. This correlation is much stronger than that found by Martinet & Friedli (1997). The regression line in Fig. 1 is given by

$$log(I_{25}/I_{100}) = -1.81 + 0.093\epsilon_b \quad (2)$$

with a correlation coefficient of 0.9. In a scheme where bar-induced star formation dominates the global star formation efficiency of the galaxy, we would expect this increase of star formation caused by the strong gas flows present in disk galaxies. Numerical models show that the shocks due to the bar are stronger when the bar strength increases (Athanassoula 1992; Friedli & Benz 1993, 1995). Also, the velocity dispersion increases and gas cloud collisions become more frequent. Some studies, such as Kennicutt (1994), conclude that the global star formation activity is comparable along the Hubble sequence for barred and normal spirals. However, this result could be due to the inadequacy of the Hubble scheme in describing the bar strength.

Fig. 2 shows the relation between $log(I_{25}/I_{100})$ and the relative projected bar length ($2L_b/D_{25}$), where L_b is the bar length and D_{25} the diameter of the 25 mag arcsec^{-2} B isophote. The data were taken from de Vaucouleurs et al. (1991). There is no clear trend in Fig. 2. However, we can bin the galaxies in three groups. The first group is formed by the galaxies with the strongest bars. This group has galaxies with the most enhanced star formation activity. These galaxies show values of $2L_b/D_{25}$ between 0.12 and 0.21. The second group consists of galaxies with $4.4 < \epsilon_b < 5.7$, and the third group includes those with $\epsilon_b < 4.4$. This latter group shows a weak correlation between ($2L_b/D_{25}$) and the star formation activity. Thus, the bigger the relative projected bar length, the more enhanced is the star formation as measured by the $log(I_{25}/I_{100})$ ratio. It can be noted that the bar strength, as measured via the ellipticity, is the parameter which has a significant influence on the star formation rate of a galaxy, because for a fixed $2L_b/D_o$ the star formation rate becomes larger when the ellipticity increases.

Unfortunately IRAS fluxes have not enough spatial resolution to resolve the distribution of the mid-IR emission. Devereux (1987) found that a large fraction ($> 40\%$) of early type barred spirals have a strong enhancement of IR emission in their central region (~ 1 kpc diameter). In this work the number of early-type barred galaxies is only 4, and the major part of the galaxies in the sample are late-type barred galaxies. For the late-type galaxies Devereux did not find any strong enhancement of mid-IR emission in their centers. Rozas et al. (1998) investigated the symmetry of the Hα brightness in barred and non-barred galaxies. They concluded that there is a greater degree of symmetry in the non-barred than in the barred galaxies. Thus the bars affect the star formation also in the outer disk. Hα images of the galaxies presented in this work are needed to investigate whether the star formation is occurring mostly in the center regions of the galaxies or whether it takes place in the outer disk.

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