Variation of Galactic Bar Length with Amplitude and Density as Evidence for Bar Growth over a Hubble Time

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ABSTRACT

K_s-band images of 20 barred galaxies show an increase in the peak amplitude of the normalized $m = 2$ Fourier component with the R_{25}-normalized radius at this peak. This implies that longer bars have higher $m = 2$ amplitudes. The long bars also correlate with an increased density in the central parts of the disks, as measured by the luminosity inside $0.25R_{25}$ divided by the cube of this radius in kpc. Because denser galaxies evolve faster, these correlations suggest that bars grow in length and amplitude over a Hubble time with the fastest evolution occurring in the densest galaxies. All but three of the sample have early-type flat bars; there is no clear correlation between the correlated quantities and the Hubble type.

Subject headings: galaxies: structure — galaxies: spiral

1. Introduction

Bars should slow down and grow over time as bar angular momentum is transferred to the disk (Tremaine & Weinberg 1984) and halo (Kormendy 1979; Sellwood 1980; Little & Carlberg 1991; Hernquist & Weinberg 1992; Debattista & Sellwood 1998, 2000; Valenzuela & Klypin 2003; Athanassoula 2002, 2003). With this growth, the bars should become stronger, longer and thinner (Athanassoula 2003).

Pattern speeds are difficult to measure (Knapen 1999) but bar lengths are not (Erwin 2005). To investigate the model predictions, we examined relative bar lengths and intensities in 20 galaxies with conspicuous bars and a range of Hubble types. We consider how these parameters correlate with each other and with the central density of the galaxy. Central luminosity density is used as an indirect measure of the inner angular rotation rate because few galaxies in our sample have observed rotation curves. Galaxies with high central densities should have high central rotation rates and evolve more quickly than galaxies with low central densities. If there is a secular change in bar length or amplitude with angular momentum transfer, then denser galaxies should show the later evolutionary stages.

2. Observations and Analysis

$K_{\rm s}$-band images of barred galaxies were obtained with the Anglo-Australian Telescope (AAT) from 2004 June 28 to July 5. We used the Infrared Imager and Spectrograph (IRIS2) with a 1024×1024 pixel Rockwell HAWAII-1 HgCdTe detector mounted at the AAT's $f/8$ Cassegrain focus, yielding a pixel scale of $0.447\,{\rm arcsec\,px^{-1}}$ and a field of view of 7.7 arcmin squared. Exposure times were around one hour in almost all cases and the angular resolution was typically 1.5 arcsec. Full details of the observations will be presented in Buta et al. (2007).

Images were pre-processed using standard IRAF[1] routines, and each image was cleaned of foreground stars and background galaxies. Deprojections were derived as follows. For each galaxy, estimates of the orientation parameters were obtained using an ellipse fitting routine,

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[1] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

sprite, originally written by W. D. Pence. These fits were either based on the K_s-band image itself, or on an optical image if available. Because the bulges may not be as flat as the disks, we used a two-dimensional multi-component decomposition code (Laurikainen, Salo, & Buta 2005) to derive the parameters of the bulges and disks. Images were deprojected, assuming the bulges are spherical, using the IRAF routine IMLINTRAN. This assumption has little impact on our Fourier analyses. The results of the decompositions, as well as the orientation parameters used, will be presented in Buta et al. (2007).

3.   Results

Bar and spiral arm amplitudes were measured from the $m = 2$ Fourier components of azimuthal intensity profiles taken at various radii from polar plots using the deprojected, star-cleaned, background-subtracted images (as in Regan & Elmegreen 1997 and Block et al. 2004). The $m=2$ Fourier intensity amplitude, I_2, was normalized to the average intensity, I_0, at each radius; I_2 is defined to be the amplitude of the sinusoidal fit to the azimuthal profile. Figure 1 shows this normalized amplitude, $A_2 = I_2/I_0$, versus the radius normalized to the standard isophotal radius R_{25} for each galaxy (R_{25} is half the diameter D_{25} of the $\mu_B = 25$ mag arcsec^{-2} isophote given by de Vaucouleurs et al. 1991). The 20 profiles have been divided into four panels for clarity. Figure 1 shows that A_2 increases with radius and then decreases. The maximum, A_2^{max}, occurs at a radius which we denote by R_2. This radius is approximately equal to the bar length determined by eye in all cases. Theory suggests the two lengths should scale together, with R_2 slightly less than the visible bar length (Athanassoula & Misiriotis 2002). A correlation may be seen in Figure 1 in the sense that galaxies with higher A_2^{max} also have larger radii at this peak (the peaks are indicated by the circles; empty circles are flat bars and circles with plus-signs are exponential bars).

This correlation is shown in Figure 2 (top left), which plots A_2^{max} versus the normalized radius R_2/R_{25}. The dashed line is a bi-variate least squares fit, repeated in the other panels. Longer bars are higher amplitude in relative intensity. This is sensible considering the general exponential decline of disk intensity: longer bars extend further out in the disk, placing their ends where the average background is fainter. For example, each radial interval of $\sim 0.25R/R_{25}$ corresponds to about one exponential scale length in most galaxies, which is a factor of 2.7 in disk brightness. This factor is only slightly larger than the increase in Figure 2. Thus, growing bars can stay somewhat flat in their intensity profile and still increase their relative amplitude along with their length because the surrounding disk is decreasing with radius. Bars apparently grow relative to the disk size even if the disk grows too because of angular momentum transfer from the bar (Valenzuela & Klypin 2003).

Figure 2 (top right) includes three previous surveys in which this correlation was present but not noticed. The crosses are from K-band images of 8 different barred galaxies studied by Regan & Elmegreen (1997), the circles are from K_s-band images of 24 different early type (S0-Sa) barred galaxies in Buta et al. (2006), and the triangles are from 10 I-band images of different galaxies in Elmegreen & Elmegreen (1985). Among these three samples, there are only 3 overlapping galaxies and they are only between the 1985 and 1997 surveys. The Regan & Elmegreen A_2^{max} values were multiplied by 2 because they used the standard definition of a Fourier component, which, for example, gives a relative value of 0.5 for an azimuthal profile of $1+\sin(2\theta)$. We and the other references in Figure 2 use twice the Fourier component to reflect the amplitude of the sinusoidal part of the profile.

The lower panels of Figure 2 show correlations present in data from two other studies of bar Fourier amplitudes. The lower left panel shows data from Laurikainen et al. (2006), who determined the Fourier amplitudes and bar radii for 28 early type galaxies (S0,Sa, Sab) in K_s band. The lower right panel shows data from Laurikainen et al. (2004), who used the Ohio State Bright Galaxy Survey and 2MASS to measure the H-band properties of 113 galaxies of various Hubble types. Their tabulations give the bar lengths, not the radii at the peak of the Fourier amplitude. Bar length is slightly larger than R_2, so the points are shifted to the right of the dashed lines in the figures. Also, A_2 is lower for S0 galaxies than other early types, which lowers some of the points in the lower left panel (Laurikainen, Salo, & Buta 2004). The present correlation was not noticed in either study but it is present in the data.

Our previous study of K_s-band images for 17 barred galaxies (Block et al. 2004) found a length-amplitude correlation related to the present one. There we plotted the bar/interbar intensity contrast at 0.7 bar length versus the deprojected length of the bar (determined by eye). There was no overlap in galaxies with the present or the Buta et al. (2006) samples, and only one overlap each with the Regan & Elmegreen (1997) and Elmegreen & Elmegreen (1985) samples. The bar/interbar intensity contrast was shown by Block et al. to correlate with the relative amplitude of the $m = 2$ Fourier component, and with the bar torque parameter, Q_b. This previous study discussed the length-amplitude correlation in a different context, however, noting that the long and high-amplitude bars tended to be early Hubble type and flat-profile, while the short and low-amplitude bars tended to be late Hubble type and exponential. This is true in general, but the present result is in addition to that. In the present work, the length-amplitude correlation is present even for the flat bars, and there is no strong correlation with Hubble type because most of our galaxies are flat-barred.

The R_2/R_{25} length is plotted versus Hubble type for our sample in Figure 3. The circled plus-signs are exponential bars, and the rest are flat bars. Most of the galaxies in our current

sample are Hubble types Sbc or earlier. The three exponential bars in our sample have slightly weaker Fourier components than the average for the flat bars (Fig. 2). Evidently, there are two length-amplitude correlations: one discussed by Block et al. differentiating early and late type bars (which is presumably related to different bar resonances; Combes & Elmegreen 1993), and another found here that remains even for early-type, flat bars. The lower right panel of Figure 2 illustrates these two correlations in another way by plotting the various Hubble types with different symbols. The late types tend to be confined to the lower left in the figure, while the early types display the full range of bar lengths and amplitudes.

Laurikainen, Salo, & Buta (2004) found no correlation between the peak relative torque, Q_g, normalized to the radial force, and the relative radius at the peak of this torque. The relative torque is a combination of the azimuthal bar amplitude, which determines the torque, and the radial force from the bulge, which is used to normalize this torque. Stronger-bulge galaxies have weaker bar torques for the same relative $m = 2$ component. Bulges do not affect the peak A_2 much because the bulge intensity at the end of the bar is small. On the other hand, bulges do affect Q_g because the radial force from the bulge is still large at the bar end.

The central luminosity densities of the galaxies were measured from the K_s-band luminosities inside $0.125R_{25}$, $0.25R_{25}$, and $0.5R_{25}$. The K_s-band is dominated by old stars and traces the mass fairly well if dark matter is not significant there. Most of the galaxies are early type and centrally condensed so the 3 luminosities measured in this way were all about equal. Because the R_2/R_{25} lengths vary from $\sim 0.1R_{25}$ to $\sim 0.5R_{25}$, and we want a representative density in the bar region, we use the luminosity inside $0.25R_{25}$. The central density is then taken to be this luminosity divided by the cube of the radius at $0.25R_{25}$, measured in kpc using the distances in Table 1 (from the galactocentric GSR in the NASA/IPAC Extragalactic Database). Figure 4 shows the central K_s-band density versus the normalized radius at the peak $m = 2$ amplitude (plus signs denote exponential bars). There is a correlation in the sense that longer bars occur in denser galaxies.

These two correlations provide new information to supplement properties found in other bar correlations. Athanassoula & Martinet (1980) and Martin (1995) found a correlation between the lengths of bars and bulges, and Elmegreen & Elmegreen (1985) found a correlation between bar length, amplitude, and early versus late Hubble types, as mentioned above (see review in Ohta 1996).

4. Discussion

We find that among fairly early type galaxies, relative bar length and relative $m = 2$ intensity correlate with each other but not obviously with the Hubble subtype. The lengths and amplitudes also correlate with the central luminosity density of the galaxy. These correlations are in the sense expected by numerical simulations which suggest that angular momentum gradually transfers from a bar to the surrounding disk, bulge, and halo (see Athanassoula 2003 and references therein). With a loss of angular momentum, bars should slow down, and this means their corotation radii move outward. The stellar orbits in the bar should also get more elongated as angular momentum is proportional to the orbital area, and this translates to ellipticity for a constant orbital energy. As the orbital ellipticity increases, the stars become more concentrated in the bar and the bar gets stronger. If the orbits also scatter in energy, then their semi-major axes should grow too, following the moving corotation resonance. In this case, bars would grow in length as they get higher relative amplitudes during angular momentum loss. This is apparently what we observe here.

The correlation with central density is consistent with angular momentum loss because galaxies with higher central densities evolve faster. In a given galaxy lifetime, the bars which evolve faster will have transferred more of their angular momentum outward and at the present time will have longer and higher-amplitude bars. The correlation with central density could also result from a larger reservoir for bar angular momentum in the larger bulges. An inverse process might be responsible too, where a strong bar forms first and this causes the bulge to grow through accretion (e.g., Athanassoula 1992, 2003).

The lack of a correlation between relative bar length and peak relative bar torque Q_g may be understood from our correlations with central density. For a given bulge, angular momentum transfer should increase both the peak amplitude and the peak torque of the bar over time. Galaxies with denser bulges do this faster, so at any given time, the peak amplitude correlates with bulge density. However, denser bulges weaken Q_g because this quantity is normalized to the radial force (Laurikainen, Salo, & Buta 2004). This normalization offsets the increasing bar amplitude that comes from angular momentum transfer. As a result, Q_g does not show the same correlations as the $m = 2$ Fourier amplitude.

Galaxies with dense bulges should not have bars if bulges prevent bar formation or growth (e.g., Sellwood 1980). However, our data show that high central densities correlate with high-amplitude bars. The observed correlation suggests that bars and bulges grow together, in agreement with Sheth et al. (2007).

5.   Conclusions

Bars in intermediate and early type spirals have a correlation between their relative lengths and their relative $m = 2$ Fourier components, and both increase with the central density. These correlations are consistent with models in which bars lose angular momentum to the surrounding disk, bulge, and halo over long periods of secular evolution. The bars contain very old stars and must have been present for a high fraction of the Hubble time, like the bulges.

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Table 1.   Barred Galaxies

Galaxy	typetablenotemarka	D (Mpc)	R$_{25}$ (arcsec)	R_2/R_{25}[b]	I_2/I_0[c]
NGC175	SB(r̲s)ab	53.9	64.1	0.2	0.33
NGC521	SB(r̲s)bc	69.6	94.9	0.15	0.18
NGC613	SB(r̲s)bc	19.8	164.9	0.5	0.4
NGC986	(R$_1'$)SB(rs)b	25.7	116.7	0.6	0.62
NGC4593	(R$_1'$)SB(rs)ab	35.6	116.7	0.5	0.48
NGC5101	(R$_1$R$_2'$)SB(r̲s)a	23.7	161.1	0.3	0.36
NGC5335	SB(r)b	63.2	64.1	0.2	0.5
NGC5365	(R)SB0$^-$	31.6	88.5	0.3	0.34
NGC6221	SB(s)bc pec	19	106.4	0.3	0.3
NGC6782	(R$_1$R$_2'$)SB(r)a	52.6	65.6	0.4	0.37
NGC6907	SAB(s)bc	44.5	99.3	0.3	0.42
NGC7155	SB(r)0°	26.7	65.6	0.3	0.31
NGC7329	SB(r)b	43.1	116.7	0.2	0.33
NGC7513	SB(s)b	21.9	94.9	0.25	0.35
NGC7552	(R$_1'$)SB(s)ab	21.7	101.7	0.55	0.6
NGC7582	(R$_1'$)SB(s)ab	21.3	150.4	0.45	0.45
IC1438	(R$_1$R$_2'$)SAB(r)a	20	72	0.3	0.385
IC4290	(R$'$)SB(r)a	64.3	47.6	0.4	0.42
IC5092	(R)SB(s)c	43.3	86.5	0.2	0.33
UGC10862	SB(rs)c	24.8	82.6	0.2	0.31

[a]Classifications are either from the de Vaucouleurs Atlas of Galaxies (Buta, Corwin, & Odewahn 2007) or estimated by RB in the same system based on available image material.

[b]Relative radius of peak relative $m = 2$ Fourier amplitude.

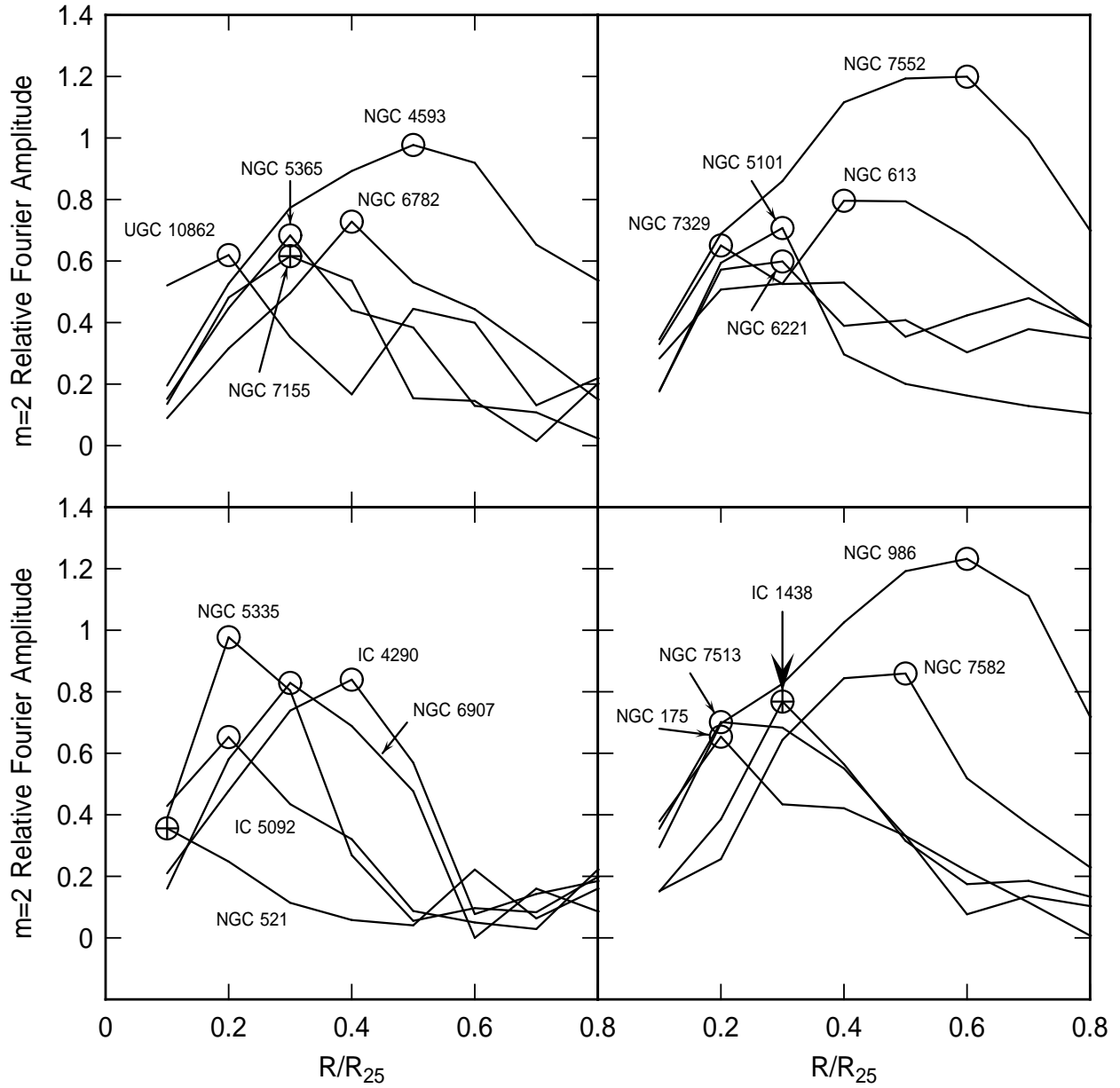[c]Peak relative $m = 2$ Fourier amplitude.

Fig. 1.— Relative amplitude of the $m = 2$ Fourier component of the bar and spiral pattern versus radius for 20 galaxies. Circles show the peaks. Circles with plus signs are bars with exponential intensity profiles, the others have relatively flat profiles.
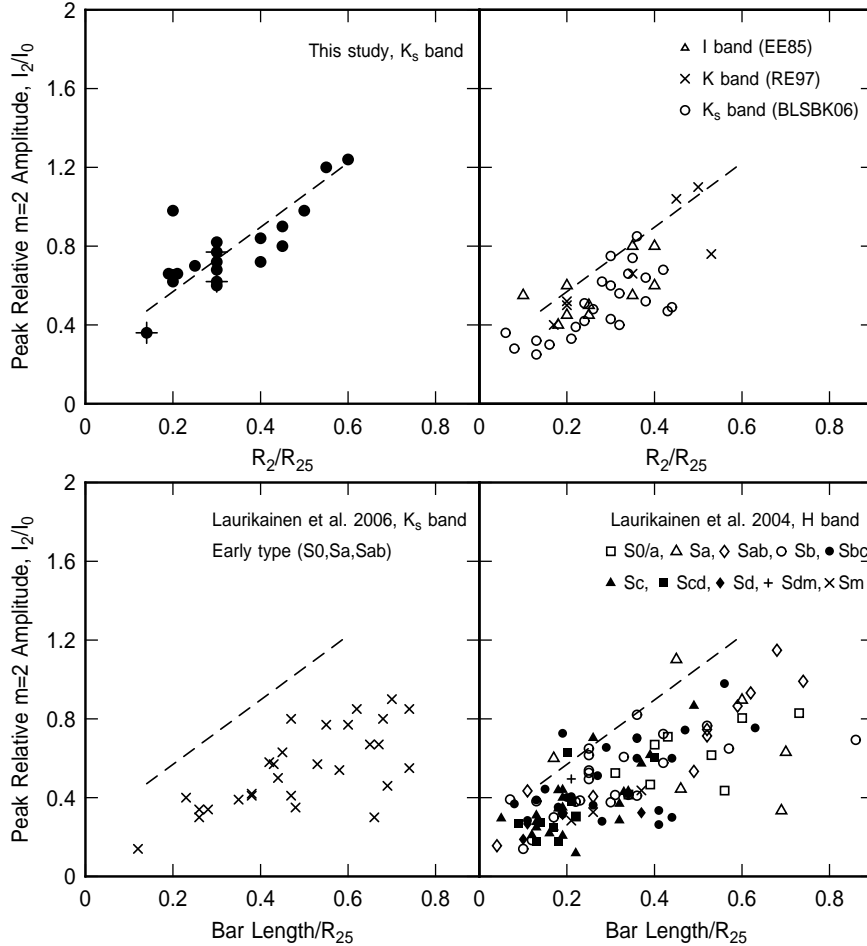
Fig. 2.— Peak relative amplitude of the $m = 2$ Fourier component versus the normalized radius at the peak. Left: galaxies in Fig. 1 all imaged in K_s band (plus signs are exponential bars). Slight displacements among a triplet at $R_2/R_{25} = 0.2$ are for clarity. Published measurements from other surveys are shown in the top right and bottom. Top right: three surveys in various passbands having little overlap with galaxies in the present study (see text). Bottom left: 28 early type (S0,Sa, Sab) galaxies imaged in K_s band in a combined southern and northern survey by Laurikainen et al. (2006). Bottom right: 104 galaxies imaged in H-band with the Ohio State Bright Galaxy Survey and 9 galaxies imaged in H-band with 2MASS, all of various Hubble types, using measurements in Laurikainen et al. (2004). All surveys indicate that bars that are longer compared to their galaxy size have higher peak relative $m = 2$ Fourier amplitudes. This correlation is present even for early type galaxies. A second, well-known correlation between bar length and Hubble type is evident from the lower right panel where the late Hubble types (solid symbols, plus and cross) tend to have shorter and weaker bars than the early types (open symbols).
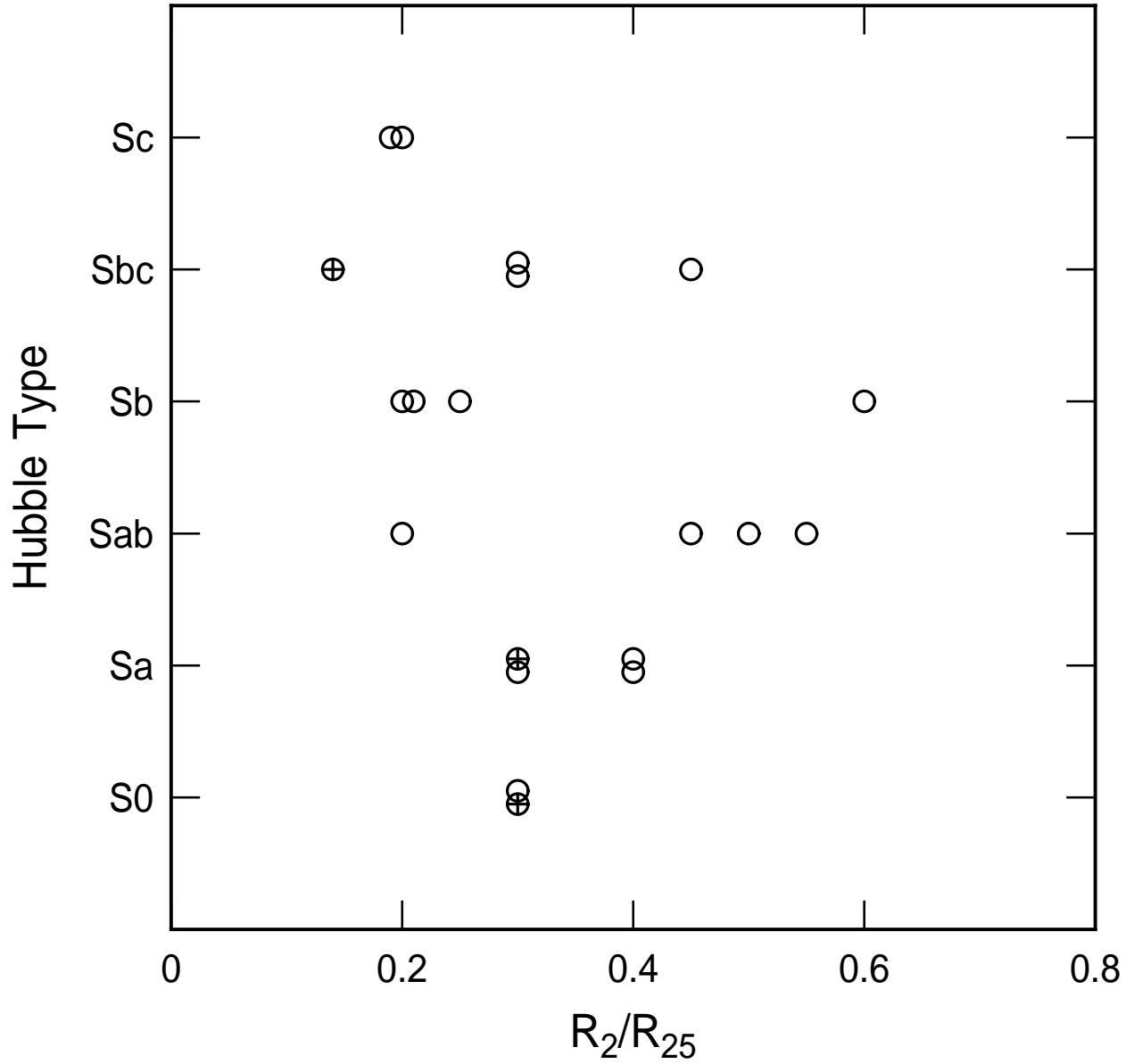
Fig. 3.— Hubble type versus the normalized radius at the peak relative $m = 2$ Fourier component (i.e., the relative bar size) showing little correlation in our sample. The circles with plus signs are galaxies with exponential bars; the rest have flat-profile bars. Slight displacements are for clarity.
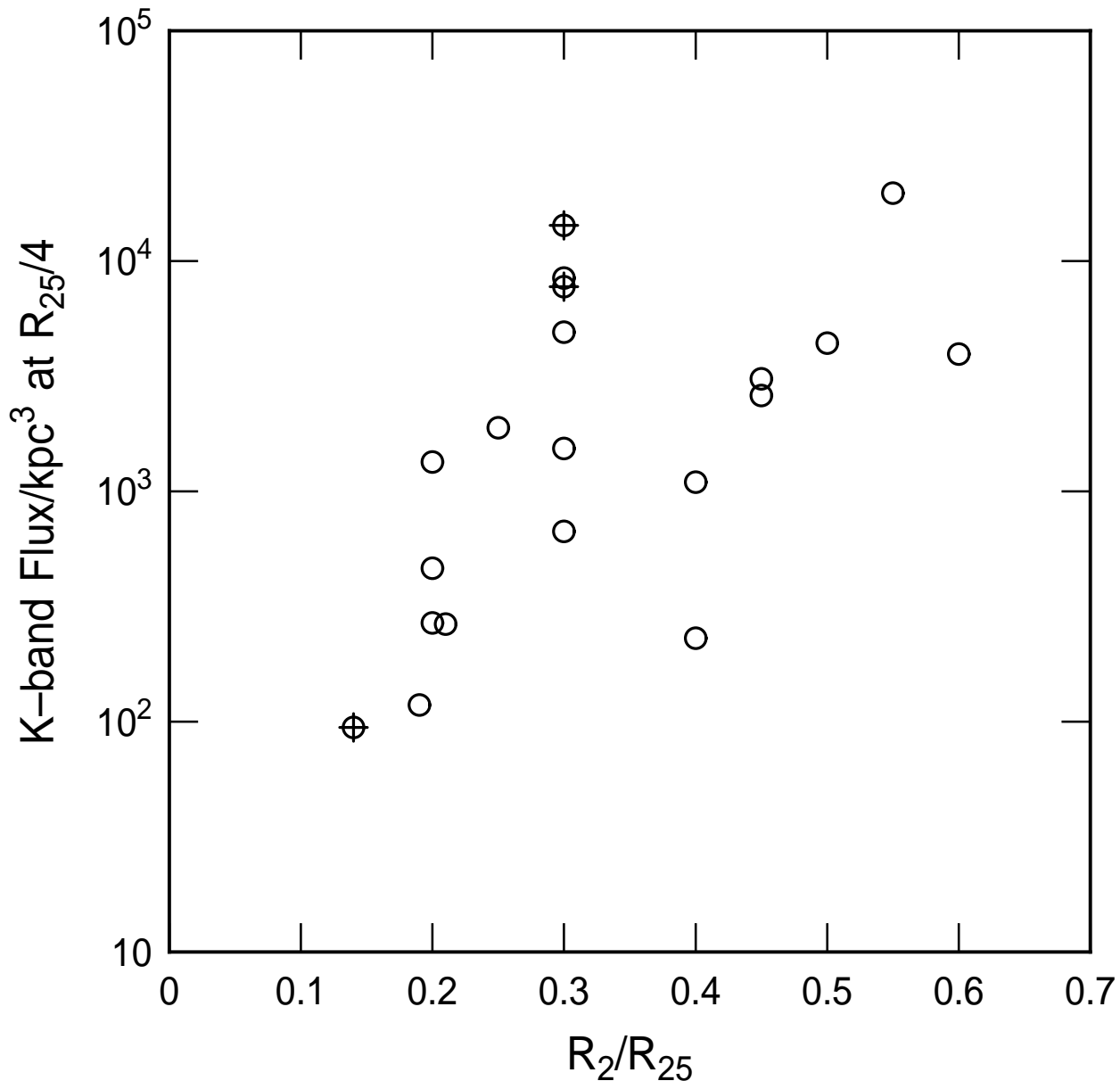
Fig. 4.— Luminosity density at $R_{25}/4$ versus the normalized radius at the peak relative $m = 2$ component. Luminosities are in units of the count rate per unit solid angle integrated inside $R_{25}/4$, and are calibrated to the same intensity scale for all galaxies. Plus signs indicate exponential bars. There is a correlation in which relatively longer bars have denser galactic centers, suggesting bar growth during a Hubble time.