

## Penetrating the Mask: All Spiral Galaxies become Barred on Bar Torque Scales between Zero and Six

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**Abstract.** The Hubble classification scheme of galaxies is based on blue-light appearance. Atlases reveal the rich variety of responses of the Population I component ('the mask') of gas and dust to the underlying, older, stellar population. However, the Population I component may only constitute 5 percent of the dynamical mass of the galaxy; furthermore, dusty masks are highly effective in hiding bars. In the 1960s, Ken Freeman presented a meticulous study of the dynamics of bars at a time when nonbarred galaxies were called "normal" spirals and barred galaxies were regarded as curiosities. Now we know that it is more "normal" for a galaxy to be barred than to be nonbarred. What is the range for the gravitational torques of bars? At which torque value is a galaxy considered 'barred'? We describe here a recently developed method for deriving relative bar torques by using gravitational potentials inferred from near-infrared light distributions. We incorporate a bar torque class into the Block/Puerari dust-penetrated galaxy classification system. We find a huge overlap in relative bar torque between Hubble (Sa, Sb, ...) and (SBa, SBb, ...) classifications and we assert that from a quantitative morphological point of view, all spiral galaxies may be considered barred, described by a bar torque parameter varying in a continuous manner, from zero to six. Application of the method to the high redshift universe is briefly discussed.

## 1. Introduction

Bars have been recognized in galaxies since the time of Curtis (1918) and Hubble (1926), although the bar-like structure of the LMC was already beautifully portrayed in a remarkable sketch by J. Herschel in 1847 (Figure 1). Other observers carefully drew bar-like structures in galaxies outside of our Local Group: e.g. Le Sueur & MacGeorge (1869); see also Gascoigne (1996). Bars are among the most interesting features of galaxies that present a clear challenge to theorists. It is not surprising, then, that bars attracted the early attention of Ken Freeman, who applied his mathematical expertise to understanding them in a remarkable series of papers published in the 1960s (Freeman 1965; 1966a,b,c). Of course, at that early stage, bars were regarded mostly as dynamical curiosities rather than representing a major topic of research, which still continues to unfold at the present time. Nevertheless, Ken pursued them initially in his Cambridge dissertation work and later developed a model of asymmetric barred galaxies in a collaborative effort with G. and A. de Vaucouleurs (de Vaucouleurs, de Vaucouleurs, & Freeman 1968).

Ken's work, in a way, culminated with his fine review of barred galaxies with Gerard de Vaucouleurs, the first really significant review of the subject (de Vaucouleurs & Freeman 1972). This long article focussed mainly on the features of late-type, asymmetric barred spirals of the Magellanic type, and also outlines an early interpretation of the nature of the inner rings of SB(r)-type galaxies in terms of a class of resonant periodic orbits. It is interesting to note that at the time of Ken's work, the status of rotation curves suggested that bars rotated as rigid bodies (see also Figure 2).

It is also remarkable that only recently have people perceived just how strong bars are in their host galaxies, that is, how significant is their forcing relative to the dominant mass components. This was previously known only in a few individual cases that had been the subject of detailed dynamical models (e.g., Lindblad, Lindblad, & Athanassoula 1996). For the general galaxy population, the quantification of bar strength in terms of forcing had to wait for the advent of routine near-infrared imaging. We have been engaged in dust-penetrated galaxy classification for some time now, and describe here a recently-developed method for quantifying the gravitational torques of bars using potentials inferred from near-IR images. Bar strength is important in galaxy morphological studies because phenomena such as gas inflow, angular momentum transfer, noncircular motions, lack of abundance gradients, nuclear activity, starbursts, and the shapes and morphologies of rings and spirals, may all be tied in various ways to the effectiveness with which a bar potential influences the motions of stars and gas in a galactic disk (e.g., Sellwood & Wilkinson 1993; Buta & Combes 1996; Knapen 1999).

## 2. Removing the Mask: Dust-Penetrated Galaxy Classification

Two hours north of Dunk Island, our meeting locale, lies the land of Papua New Guinea. It is the country where masks still dance. Customs have remained unchanged for centuries. Where men and women, as if from the stone age, meet the New Millennium. In Roget's Thesaurus, we find the following:

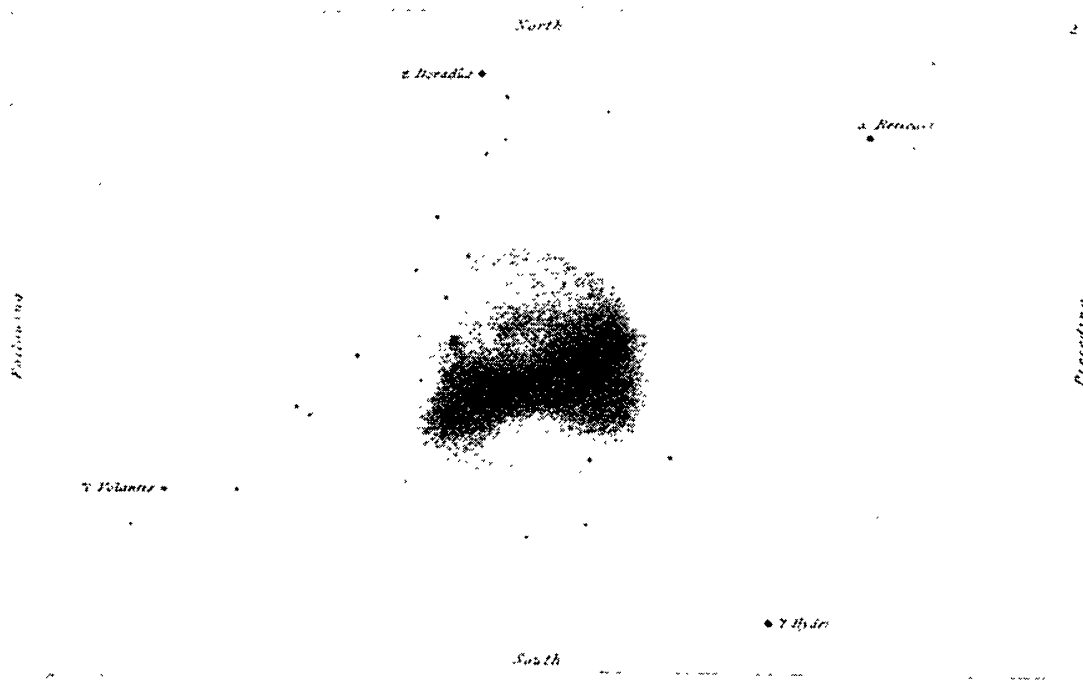


Figure 1. The bar in the Large Magellanic Cloud is beautifully portrayed in this naked eye drawing by Sir John Herschel in 1847. Reproduced in de Vaucouleurs & Freeman (1972).

**Mask:** [noun] screen, cloak, shroud. [verb] to camouflage, to make opaque, to disguise.

Optically thick dusty domains in galactic disks can completely camouflage or disguise underlying stellar structures. *Cosmic dust grains act as masks.* The dust masks obscure whether or not the dust lies in an actual screen or is well intermixed with the stars. The presence of dust and the morphology of a galaxy are inextricably intertwined: indeed, the morphology of a galaxy can completely change once the Population I disks of galaxies – the masks – are dust penetrated (e.g., Block & Wainscoat 1991; Block et al., 1994, 2000).

The classification of galaxies has traditionally been inferred from photographic or CCD imaging shortward of the  $1\mu m$  window, where stellar Population II disks are not yet dust-penetrated. Images through an *I* ( $0.8\mu m$ ) filter can still suffer from attenuations by dust at the 50% level. The NICMOS and other near-infrared camera arrays offer unparalleled opportunities for deconvolving the Population I and II morphologies, because the opacity at *K* – be it due to absorption or scattering – is always low. The extinction (absorption+scattering) optical depth at *K* is only 10% of that in the V-band.

Many years before the advent of large format near-infrared camera arrays, it became increasingly obvious from rotation curve analyses that optical Hubble type is not correlated with the evolved Population II morphology. This was already evident in the pioneering work of Zwicky (1957) when he published his famous photographs showing the ‘smooth red arms’ in M51. In the *Hubble Atlas* and other atlases showing optical images of galaxies, we are looking at masks: at



Figure 2. Like the human frame, bars do not behave as a rigid body. To demonstrate this point clearly is Ken Freeman, seen here with body parts moving differentially to the thundering rhythm of drums in Africa. Photo by J. Mayo Greenberg, reproduced from the Kluwer volume *'Toward a New Millennium in Galaxy Morphology'* (eds. D. L. Block, I. Puerari, A. Stockton and D. Ferreira, Dordrecht 2000).

the gas, not the stars, to which the properties of rotation curves are inextricably tied.

### 3. A duality in spiral structure

There is a fundamental limit in predicting what an evolved stellar disk might look like (Block et al. 1994, 2000). The greater the degree of decoupling, the greater is the uncertainty. The fact that a spiral might be flocculent in the optical is very important, but it is equally important to know whether or not driving the dynamics is a grand design old stellar disk.

Decouplings between stellar and gaseous disks are cited in many studies including Grosbøl & Patsis (1998), Elmegreen et al. (1999), Block et al. (2000) and Puerari et al. (2000). The Hubble type of a galaxy does not dictate its dynamical mass distribution (Burstein & Rubin 1985). This is confirmed by examining Fourier spectra, for example, of the evolved disks of NGC 309 (Sc) and NGC 718 (Sa); these spectra are almost identical (Figs. 11 and 12 in Block et al. 2001a).

#### 4. Bar Strength: the 60s versus the 00s

In the 60s, bar strength was something that was judged visually on blue-light photographs. Galaxies were recognized as either S or SB in Hubble's (1926, 1936) system, or as SA, SAB, SB in de Vaucouleurs' (1959) revised Hubble system. It was assumed that an SB galaxy has a stronger bar than an S galaxy, and that the sequence SA-SAB-SB was a sequence of increasing average bar strength. However, neither the Hubble nor the de Vaucouleurs bar classifications can be expected to be accurate measures of bar strength in individual cases because apparent bar strength is impacted by wavelength, the effects of extinction and star formation, inclination and bar orientation relative to the line of sight, and also on observer interpretations. The percentage of unbarred galaxies in the *Carnegie Atlas* dramatically drops from 70% to only 27% when Sa, Sb, Sc spirals are mask-penetrated (Eskridge et al. 2000; see also Knapen, Shlosman & Peletier 2000, Block & Wainscoat 1991). Thus, the near-IR is the best wavelength regime for quantifying the strength of bars. A simple, easily reproducible quantitative near-infrared morphological classification scheme for spirals that accounts for bar strength, dominant harmonic, and arm pitch angle class has been proposed by Block & Puerari (1999) and Buta & Block (2001) and is seen in Figure 3.

#### 5. Bar Strengths Derived from Gravitational Torques

Any reliable measure of bar strength ought to involve forces, because this is how the influence of a bar is actually felt. Unlike the axisymmetric background, a bar involves both radial and tangential forces. The most elegant definition of bar strength in terms of these force components was proposed by Combes & Sanders (1981). Given the gravitational potential  $\Phi(R, \theta)$  in the disk plane, these authors defined the bar strength at radius  $R$  as

$$Q_T(R) = \frac{F_T^{max}(R)}{F_0(R)} = \frac{1}{R} \left( \frac{\partial \Phi(R, \theta)}{\partial \theta} \right)_{max} \frac{d\Phi_0(R)}{dR} \quad (1)$$

where  $F_T^{max}(R)$  represents the maximum amplitude of the tangential force and  $F_0(R)$  is the mean axisymmetric radial force, inferred from the  $m=0$  component of the gravitational potential. In this approach, the strength of the bar is measured relative to the axisymmetric forces of the background disk. A relatively thin bar imbedded in a massive axisymmetric disk may have significant tangential forces, but relative to the background radial force field, it could be weak. Thus, measuring bar strength as a force ratio (rather than an isophotal axis ratio) is an idea whose time has come. Our gravitational potentials are derived from near-IR images under the assumptions of a constant mass-to-light ratio and an exponential vertical scale height (Quillen, Frogel, & González 1994).

A tangential-to-radial force ratio map reveals a butterfly pattern that is the characteristic signature of a bar (see Figure 4, adapted from Buta & Block 2000). The actual force ratio changes sign from quadrant to quadrant relative to the bar axis, because the total force in the plane is slightly offset towards the ends of the bar. In the case of perfect symmetry,  $|Q_T|$  would reach a maximum at the same radius and angle relative to the bar in each quadrant. However, slight



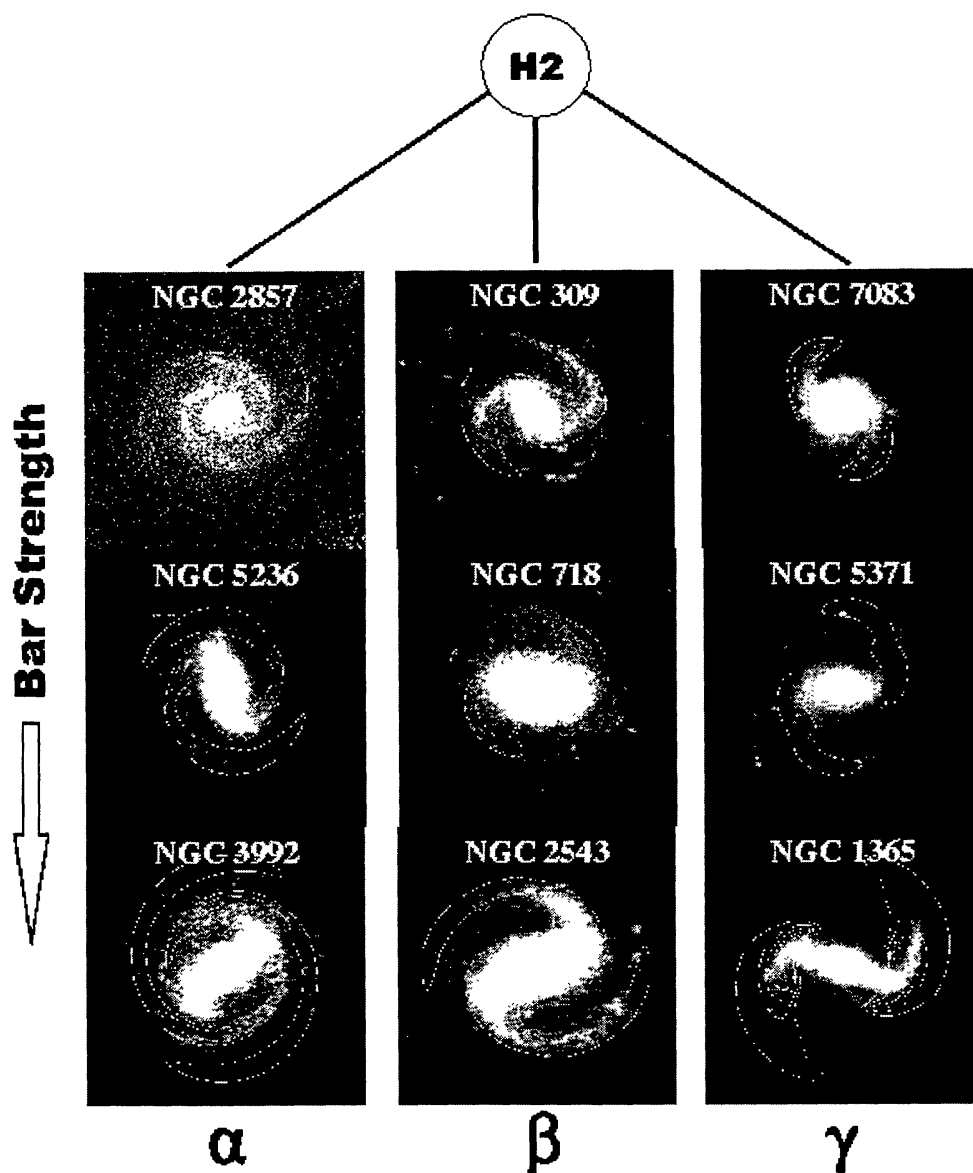


Figure 3. Spiral galaxies in the dust penetrated regime are binned according to three quantitative criteria:  $Hm$ , where  $m$  is the dominant Fourier harmonic (illustrated here are the two-armed  $H2$  family); the pitch angle families  $\alpha$ ,  $\beta$  or  $\gamma$  and thirdly the bar strength, derived from the gravitational torque (not ellipticity) of the bar. Early type b spirals (NGC 3992, NGC 2543, NGC 7083, NGC 5371 and NGC 1365) are distributed within all three families ( $\alpha$ ,  $\beta$  and  $\gamma$ ). Hubble type and dust penetrated class are uncorrelated.

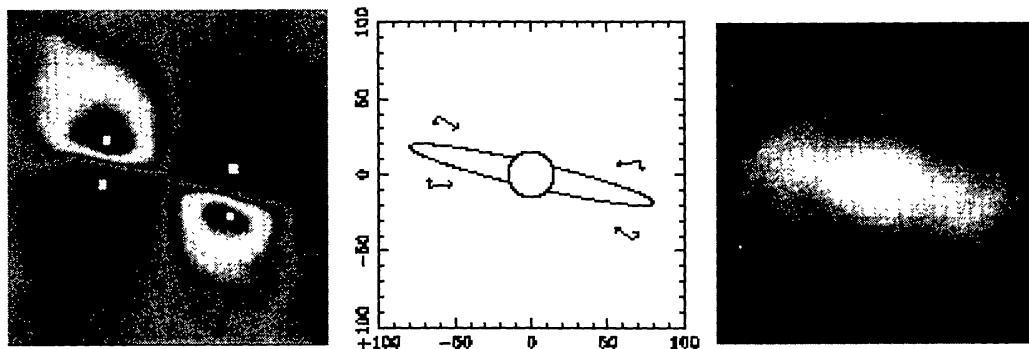


Figure 4. The characteristic signature of a bar is this ratio map, or butterfly pattern. The map shows four well-defined regions where the tangential-to-radial force ratio reaches a maximum or minimum around or near the ends of the bar. Seen at left is the ratio map for NGC 1433; the galaxy appears at right. The sign of the tangential force changes from quadrant to quadrant (central schematic) and absolute values are considered in our gravitational bar torque method.

asymmetries and/or noise can make these maxima different in each quadrant. If we let  $Q_{bi} = |Q_T|^{max}$  in quadrant  $i$ , then the average of these four values can provide a single measure of bar strength for a whole galaxy, if the gravitational potential is known. We call this average the *relative bar torque parameter*,  $Q_b$ . The  $Q_{bi}$  are known as the “maximum points.”

Bar torque classes are defined in terms of intervals of  $Q_b$ . Bar class  $B_c=1$  includes galaxies having relative torques  $Q_b = 0.1 \pm 0.05$  (meaning the tangential force reaches a maximum of 10% of the axisymmetric background radial force); class 2 involves those with  $Q_b = 0.2 \pm 0.05$ , etc., up to class 6 (Buta & Block 2001).

Uncertainties in the bar torque method are discussed in Buta & Block (2001). These include simple deprojection uncertainties, such as bulge “deprojection stretch”, as well as more complex uncertainties, such as variations in the stellar mass-to-light ratio with position, the impact of dark matter and bulge thickness, vertical resonances and the thickening of bars, and the generally unknown vertical scale heights of disks. Future studies will involve evaluating these uncertainties further and refining the method.

## 6. Hubble Classifications and Bar Torques

From our studies (Buta & Block 2001; Block et al. 2001b), we have estimates of  $Q_b$  for 75 galaxies at this time. Figure 5 shows how this parameter correlates with optical bar classification in the Revised Shapley-Ames Catalogue (RSA, Sandage & Tammann 1981). A wide range of relative bar torques characterizes each of the S and SB categories. Category S (i.e., optically unbarred) in Fig. 5 includes galaxies ranging from bar torque class 0 (e.g., NGC 628) to bar class 3 (e.g., NGC 1042). NGC 4321, a Hubble Sc prototype, has a bar class of 2. Likewise, NGC 4450 (Sab) is of bar class 2.

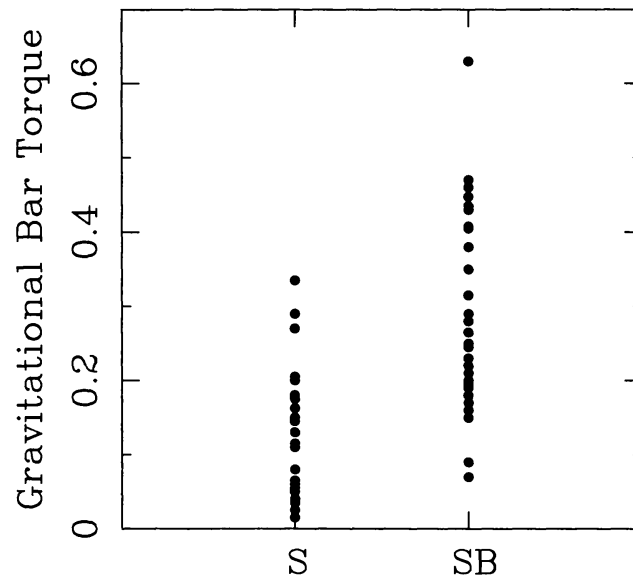


Figure 5. The threshold for calling a galaxy “SB” is bar torque class 1 (where  $Q_b$  ranges from 0.05 to 0.149). NGC 5371 (Sb/SBb) is an example of bar torque 1. The Hubble classification does not make any further discrimination on bar strength  $Q_b$  beyond this threshold. We find that the bars with the strongest gravitational torques reach a bar class of 6, where the maximum tangential force reaches about 60% of the mean radial force. Further details in Block et al. (2001b).

Similarly, Hubble category SB in the RSA has a wide range of bar strengths. This category commences at a bar torque of class 1 (e.g., NGC 5371) and reaches bar class 5 (e.g., NGC 7741) and class 6 (e.g., NGC 7479). In other words, the bar strengths of some RSA SB galaxies may be *weaker* than those found in RSA unbarred spirals such as NGC 1042 (Sc; near-infrared bar class 3). This is not due to the uncertainties in the  $Q_b$  method, but instead reflects the difficulties of making reliable bar strength judgments in the visual Hubble system. The work of Knapen et al. (2000) reaches this identical conclusion, using their independent definition of bar strength.

Martin (1995) classified bars according to *shape of isophotes*. One of the strongest classes in Martin’s sample is bar ellipticity class 7. It is interesting to note that highly elliptical bars as measured by Martin (1995) need *not* have strong gravitational bar torques (see Figure 6).

## 7. Toward the future: Choice of instruments for NGST and Dust penetrated morphology in the high-redshift universe

HDF morphology preferentially samples restframe UV light. Does the duality of spiral structure, found in our local Universe (section 2) persist at higher  $z$ ? In order to explore the capability of NGST for undertaking stellar (as opposed to gaseous) morphology studies in the higher redshift universe, Block et al. (2001a) present NASA-IRTF and SCUBA observations of NGC 922, a chaotic



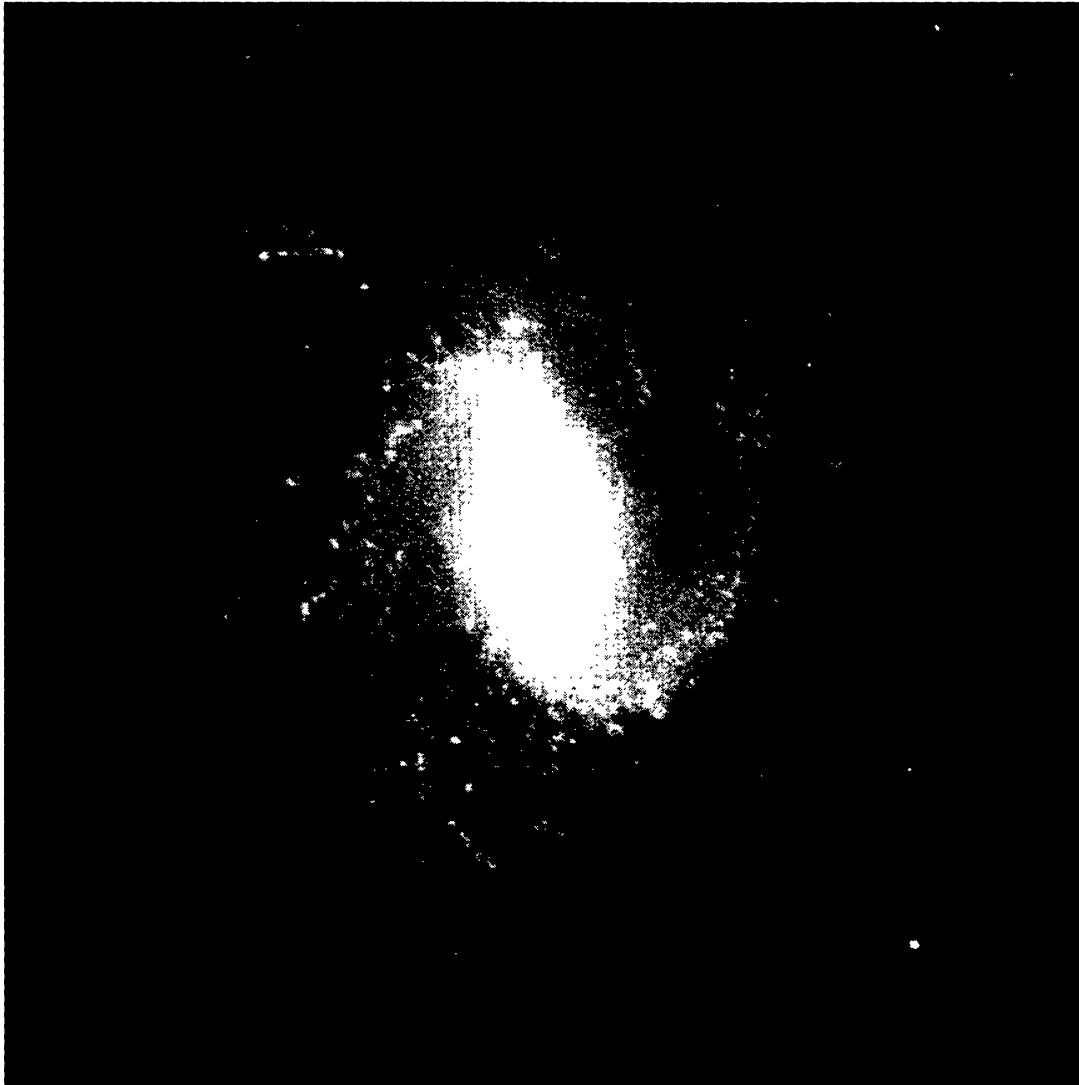


Figure 6. A near-infrared image of NGC 5236 (M83) courtesy O. K. Park and K. Freeman, shows a highly elongated bar. Martin (1995) assigns the bar of M83 to his strong bar ellipticity class 7. The gravitational bar torque of M83 is, however, weak (bar torque class 2). The tangential forces in the environs of the bar in M83 only reach a maximum of  $\sim 20\%$  of the background mean axisymmetric radial force, whereas for galaxies with truly strong bar torques, these may reach maxima of 60%.

system in our local Universe which bears a striking resemblance to objects such as HDF 2-86 ( $z = 0.749$ ) in the HDF North. If objects such as NGC 922 are common at high-redshifts, then this galaxy may serve as a local morphological ‘Rosetta stone’ bridging low and high-redshift populations. Block et al. (2001a) show that quantitative measures of galactic structure are recoverable in the rest-frame infrared for NGC 922 seen at high redshifts using NGST, by simulating the appearance of this galaxy at redshifts  $z=0.7$  and  $z=1.2$  in rest-frame  $K'$ . *Our results suggest that the capability of efficiently exploring the rest-wavelength IR morphology of high- $z$  galaxies should probably be a key factor in deciding the final choice of instruments for the NGST.*

## 8. Concluding Thoughts: Freeman and Ornithology

The work of Ken Freeman in bars and galaxy dynamics may be likened to his great passion for ornithology. Species such as *Aquila Rapax* (the Tawny Eagle) and *Aquila Nipalensis* (the Steppe Eagle) survey their terrain with exceptionally keen foresight. Ken recognised the fundamental nature of bars three decades ahead of the commissioning of large format HgCdTe arrays in the early 1990s.

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## Discussion

*Norman:* What percentage of spiral galaxies are barred?

*Sellwood:* All spiral galaxies are barred!

*Block:* Jerry has answered Colin's question succinctly. Indeed, there is no longer any separation between 'normal' and 'barred' spirals. Is a bar torque class 2 spi-

ral ‘unbarred’ or ‘barred’? In this talk, we have shown that a quantifiable and continuous bar torque class parameter may be determined for a spiral galaxy; the separation of two distinct classes ‘unbarred’ vs. ‘barred’ falls away. In that sense, Jerry is correct; all spiral galaxies are barred, described by a bar torque parameter ranging from zero to six. To emphasize this point yet further, I refer to Figure 7.

*Kormendy:* There are many published measurements of non-circular velocities in HI; these should, I would think, be driven by just the sort of non-axisymmetries in the stars that are measured by your  $Q_b$  parameter. Have you checked whether the amplitudes of noncircular HI velocities correlate with  $Q_b$ ? In particular, do they correlate better with  $Q_b$  than with optical measures of bar strength?

*Block:* A very interesting question indeed, which we have not yet investigated. One concern is that while a rich data set of non-circular HI velocity measurements exist, as you point out, these may not be at the spatial resolution we would really need. A thoughtful suggestion, John, meriting careful further study.

*Bosma:* Do the new bars you find in the near-infrared data have the same ratio of bar length to optical radius as the classic bars? I get the impression that amongst them there are a lot more small bars in the central parts of the galaxies?

*Block:* Dust is highly effective in hiding smaller bars. You are correct – it would be exceedingly rare to find dust obscuring a very long bar such as in NGC 1300, where the bar length occupies a very large percentage of the optical radius. (As an aside, the notion – at least, to me – of ‘a classic bar’, is now difficult to retain. In what sense would the near-infrared bar in NGC 4321, a Hubble Sc prototype, not be considered ‘classic’?) To probe your question further: the reason we work with bar-torque (as opposed to bar-length) is that the gravitational bar torque depends sensitively on other parameters too – such as strength of the bulge, as well as on the distribution of mass in the disk. Bars found in the Hubble type S class range from 0 (e.g., NGC 628) to bar class 3 (e.g., NGC 1042). While your impression is correct that dust does not usually hide very long bars, it can mask strong bars; the gravitational influence of bars unmasked in near-infrared images may be appreciable, as our Figure 5 illustrates.

*Athanassoula:* Barred galaxies do not have uniform vertical thickness all over the face of the galaxy. For example, bulges stick out further from the equatorial plane than discs. Similarly the ends of the bar extend further vertically than its central parts. How does this affect your bar strength quantification? In particular we should remember that there is good evidence for a correlation between the bar and the peanut strength (e.g., Lütticke et al. 2001; Athanassoula & Misiriotis 2001).

*Block:* In our preliminary analysis, we have indeed assumed that each bar and bulge is as flat as the disk. If the light distribution of a spherical bulge, for example, is transformed into a potential assuming it is a thin disk, then the axisymmetric radial forces derived will be too large, especially in the very central



Figure 7. Two hours north of Dunk Island are the Asaro Mudmen, reminding us that astronomers, like anthropologists, need to ‘penetrate masks’ to study ‘true’ morphological structure. Photo: David L. Block, Goroka, Eastern Highlands Province, PNG. Featured is USA Anthropologist Sharon Kemp, Asaro Village.

regions. As long as the bulge-dominated region is well inside the ends of the bar, this effect is minimal (Buta & Block 2001). I would also like to point out that our bar torque determinations, per galaxy, is the mean of three separate runs; in each galaxy, we vary the vertical scaleheight from 225 to 425 parsecs. If the disk were modelled as a slab of vertical scaleheight 225 parsecs with a bar whose ends extend upward to a vertical scaleheight of 425 parsecs, such variations would have little or no impact on the measured bar strength. By little, I mean one bar torque class, at most.

*Allen:* Is there a correlation between your bar torque class and the amount of light contained in the bar? Would your strongly barred torque examples contain more bar light?

*Block:* I believe the answer is no, for the following reason. Bars that are strong in terms of the  $m=2$  Fourier component of the optical light distribution (Elmegreen & Elmegreen 1985, MNRAS, 288, 438) can have either small *or large* relative torques, depending on the relative mass of the bulge. If the bulge is weak, then even an optically ‘weak’ bar (e.g., NGC 1073) can have a strong torque compared to the radial component of the force.