The Duality of Spiral Structure, and a Quantitative Dust Penetrated Morphological Tuning Fork at Low and High Redshift

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Abstract. In the near-infrared, the morphology of older star-dominated disks indicates a simple classification scheme (1) $H_m$ where $m$ is the dominant harmonic, (2) a pitch angle (derived from the Fourier spectra) associated with the rate of shear $A/\omega$ in the stellar disk and (3) a ‘bar strength’ parameter, robustly derived from the gravitational potential or torque of the bar. A spiral galaxy may present two radically different morphologies in the optical and near-infrared regime; there is no correlation between our quantitative dust penetrated tuning fork and that of Hubble. Applications of our $z \sim 0$ Fourier template to the HDF are discussed using $L$ and $M$ band simulations from an 8-m NGST; 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.

1. Introduction

There is a fundamental limit in predicting what an evolved stellar disk might look like (Block et al. 1999). 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 Grosbol & Patsis (1998), Elmegreen et al. (1999), Block et al. (1999) and Puerari et al. (2000). The Hubble type of a galaxy does not dictate its dynamical mass distribution (Burstein & Rubin 1985). For example, the Fourier spectra of the evolved disks of NGC 309 (Sc) and NGC 718 (Sa) are almost...
identical and both galaxies belong to the same β bin (see Figs. 1 and 2; both NGC 309 and NGC 718 are illustrated in Fig. 2).

2. Bar Strengths Derived from Gravitational Torques

The most elegant way of measuring bar strength is based on a definition given by Combes & Sanders (1981). The methodology uses the gravitational potential $\Phi(R, \theta)$ of the bar embedded in a disk and they define the bar strength at radius $R$ as

$$Q_T(R) = \frac{F_{T, \text{max}}(R)}{< F_R(R) >}$$

where $F_{T, \text{max}}(R) = (\partial \Phi(R, \theta)/\partial \theta)_{\text{max}}$ represents the maximum amplitude of the tangential force at radius $R$ and $< F_R(R) > = R(d\Phi_0/dR)$ is the mean axisymmetric radial force at the same radius, derived from the $m = 0$ component of the gravitational potential. Let $Q_{bi}$ be the value of $Q_{T, \text{max}}$ in quadrant $i$. Then we define the bar strength as

$$Q_b = \frac{1}{4} \sum_{i=1}^{4} Q_{bi}/4.$$  

Seven gravitational bar strength classes, from class 0 (no bar) to 6 (strongest), are elucidated by Buta & Block (2001). Galaxies classified as ‘SB’ in Fig. 3 span a wide range of bar strengths, from class 2 to class 6. Apparently ‘strong’ highly elongated bars (e.g. M 83, Fig. 1) may only have a weak gravitational potential bar class (Fig. 2).

3. A Dust Penetrated Tuning Fork

Galaxies are firstly binned according to the dominant Fourier harmonic $H_m$; all galaxies illustrated in Fig. 2 have a regular two-armed ($m = 2$) morphology. Higher order harmonics $H_3$ (e.g. NGC 5054, Fig. 1) and $H_4$ are recognised, but rarer. A ubiquity of $m = 1$ and $m = 2$ spirals in the near-infrared is found (Block et al. 1994). Galaxies are further subdivided into three dust penetrated groups ($\alpha$, $\beta$ and $\gamma$) based on the pitch angle of the arms derived from the Fourier spectra (Block & Puerari 1999). These classes are inextricably related to the rate of shear in the stellar disk, as determined by $A/\omega$ (Block et al. 1999; Fuchs, this volume). Here $A$ is the first Oort constant and $\omega$ is the angular velocity. The final quantitative morphological parameter is the bar strength.

For the galaxies illustrated in Fig. 2, the bar strengths as deduced from their gravitational potentials, are 1 (NGC 2857), 2 (M 83), 4 (NGC 3992), 1 (NGC 309), 2 (NGC 718), 3 (NGC 2543), 0 (NGC 7083), 2 (NGC 5371) and 5 (NGC 1365). M 83 is thus fully classified as H2$\alpha$2. H2$\alpha$2 = 2-armed spiral; ‘$\alpha$’: tightly wrapped arms and the final number indicating a bar strength here of 2. NGC 1365, with two wide open arms, is classified as H2$\gamma$5.
Figure 1. Pitch angle classes in the near-infrared regime, as derived from Fourier spectra (Block & Puerari 1999). The top row shows two tightly wrapped class $\alpha$ spirals (M 83 = NGC5236 and NGC 3223); the middle row shows two intermediate class $\beta$ types (NGC 5248 and NGC 4062), while NGC 5054 and NGC 5921 (bottom row) belong to the very open $\gamma$ spiral arm bin. Inverse Fourier transform contours are overlayed. Adapted from Block et al. (1999) and Puerari et al. (2000).
Spiral galaxies in the dust penetrated regime are binned according to three quantitative criteria: $H_m$, 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.
The threshold for calling a galaxy ‘SB’ is ∼ bar torque class 2 ($Q_b$ ranges from 0.15 to 0.249 for class 2). The Hubble-de Vaucouleurs classifications do not make any further discrimination on bar strength $Q_b$ (see Eq. 2) 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. Galaxies classified as ‘SA’ or ‘SAB’ mostly range from classes 0 to 2. Further details in Buta & Block (2001).
NGC 922 (imaged here in blue light) bears a striking resemblance to objects such as HDF2-86 ($z = 0.749$) in the HDF. Although NGC 922 falls outside traditional classification systems, it can readily be classified in the near-infrared template in Fig. 2. Dust penetrated imaging shows that a simple two-armed spiral (betraying the signature of arm modulation found in several grand design prototypes such as Messier 81) is largely responsible for the stellar backbone of NGC 922. The bisymmetric spiral ($m = 2$) in NGC 922 is classified as H$_2$$\gamma$ and the complete morphological classification would be H$_2$$\gamma$2 since its gravitational bar strength is 2. For further details, see Block et al. (2001).
Figure 5. Upper left: Ground-based $K'$ image of NGC 922, secured by Alan Stockton at Mauna Kea. Upper right: $K'$ image with $m = 1$ and $m = 2$ Fourier modes overlayed, as determined from the inverse Fourier transform. Middle left: Simulated 3600s image of NGC 922, moved out in redshift space to $z = 0.7$ ($L$ band) using an 8-m NGST and the prescription of Takamiya (1999). Middle right: $L$-band image, with $m = 1$ and $m = 2$ contours overlayed. Bottom right and left shows the galaxy redshifted to $z = 1.2$ ($M$ band) with and without inverse Fourier transform contours. The $M$-band postage stamp FITS images are only 3″ on a side, but Fourier spectra can easily be generated from them. Adapted from Block et al. (2001).
4. Dust Penetrated Morphology in the High-redshift Universe: Clues from NGC 922

The tuning fork in Fig. 2 may serve as a z=0 template when galaxies at \( z \sim 0.5-1 \) are imaged in their dust penetrated 2\( \mu m \) regime. Results from the Hubble Deep Field (HDF) North and South show a large percentage of high-redshift galaxies whose appearance falls outside traditional classification systems. The nature of these objects is poorly understood, but sub-mm observations indicate that at least some of these systems are heavily obscured (Sanders 1999). This raises the intriguing possibility that a physically meaningful classification system for high-redshift galaxies might be more easily devised at rest-frame infrared wavelengths, rather than in the optical regime. Practical realization of this idea will become possible with the advent of the Next Generation Space Telescope (NGST).

In order to explore the capability of NGST for undertaking such science, Block et al. (2001) present NASA-IRTF and SCUBA observations of NGC 922, a chaotic 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. (2001) 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 \( K' \) (Fig. 5). 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.

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