Toward a dust penetrated classification of the evolved stellar Population II disks of galaxies

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Abstract. To derive a coherent physical framework for the excitation of spiral structure in galaxies, one must consider the co-existence of two different dynamical components: a gas-dominated Population I disk (OB associations, HII regions, cold interstellar HI gas) and an evolved stellar Population II component. The Hubble classification scheme has as its focus, the morphology of the Population I component only. In the near-infrared, the morphology of evolved stellar disks indicates a simple classification scheme: the dominant Fourier m-mode in the dust penetrated regime, and the associated pitch angle. On the basis of deprojected K' (2.1µm) images, we propose that the evolved stellar disks may be grouped into three principal dust penetrated archetypes: those with tightly wound stellar arms characterised by pitch angles at K' of ~ 10° (the α class), an intermediate group with pitch angles of ~ 25° (the β class) and thirdly, those with open spirals demarcated by pitch angles at K' of ~ 40° (the γ bin).

There is no correlation between our dust penetrated classes and optical Hubble binning; the Hubble tuning fork does not constrain the morphology of the old stellar Population II disks. Any specific dust penetrated archetype may be the resident disk of both an early or late type galaxy. The number of arms and the pitch angle of the arms at K' of the early-type 'a' spiral NGC 718 are almost identical to those for the late-type 'c' spiral NGC 309. We demonstrate that galaxies on opposite ends of the tuning fork can display remarkably similar evolved disk morphologies and belong to the same dust penetrated class. Furthermore, a prototypically flocculent galaxy such as NGC 5055 (Elmegreen arm class 3) can have an evolved disk morphology almost identical to that of NGC 5861, characterised in the optical as having one of the most regular spiral patterns known and of Elmegreen class 12. Both optically flocculent or grand design galaxies can reside within the same dust penetrated morphological bin. As was suggested by Block et al. (1994a), it is the gas dominated Population I component which determines the optical types (a, b, c), decoupled from the Population II.

Those L=lopsided galaxies (where m=1 is a dominant mode) are designated L₀, L₉ and L₇ according to the dust penetrated pitch angle; E=evensided galaxies (where m=2 is the dominant Fourier mode) are classified into classes Eₐ, E₉ and E₇, according to our three principal dust penetrated archetypes. The L and E modes are the most common morphologies in our sample, which spans a range of Hubble types from early (a) to late (irregular). Having formulated our dust penetrated classification scheme here, we have tested it on an independent sample of 45 face-on galaxies observed in the near-infrared by Seigar and James (1998a, b).

Key words: Galaxies: fundamental parameters - Infrared: galaxies - Galaxies: stellar content - Galaxies: spiral - Galaxies: structure - Galaxies: general

1. Introduction

There was a time when there appeared to be very little interconnection between the presence and evolution of dust grains on the one hand, and galaxy morphology on the other. This has now changed so dramatically, that an entire International Conference was recently devoted to the interrelation between these two apparently discrepant disciplines (see Block 1996).

Allen (1996) summed it up thus:

“We’re now looking at a transition to a possible change in the way we look at galaxies. Sometimes ... we see disks that have a spiral structure that we couldn’t have dreamt existed from looking at the optical picture ... we’ve got a possibility here of applying the morphology to a physical framework, perhaps in a way that none of us could have dreamt of before we had the capability of sweeping the dust away from the galaxy in a figurative sense”.

Optically thick dusty domains in galactic disks can completely obscure underlying stellar structures. The presence of dust and the morphology of a galaxy are inextricably intertwined: indeed, the morphology of a galaxy can completely change once the disks of galaxies are
dust penetrated (eg. Block and Wainscoat 1997; Block, Elmegreen and Wainscoat 1996).

The distribution of dust grains in the bulges and disks of galaxies may be very widespread (Block et al. 1994b), even extending to the outer parts of galaxies (Lequeux and Guélin 1996). The tracing of dust grains in nature can be very elusive: high levels of dust extinction do not necessarily imply that the effects of dust attenuation (ie. observed reductions in surface brightness profiles) will also be large, because scattering by dust grains may fill in at least part of the lost surface brightness. The effective albedo of dust grains in the near-infrared can actually be higher than in the optical (for a determination of the near-infrared albedo of grains in M51, see Fig. 4 in Block 1996).

Furthermore, large amounts of dust do not necessarily imply red V-K (K: 2.2μm) colours. The dust column density on the far side of an inclined spiral with relatively blue V-K colours can be just as high as on the near side, where the V-K colour distribution can be much redder (Elmegreen and Block 1998).

The classification of galaxies has traditionally been inferred from photographs/CCD imaging shortward of the 1 micron window, where stellar Population II disks are not yet dust penetrated. The NICMOS and other near-infrared camera arrays offer unparralleled 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 (Martin and Whittet 1990).

From a dynamical viewpoint, the disk of a spiral galaxy can be separated into two distinct components: the gas-dominated Population I disk, and the star-dominated Population II disk. The former component contains features of spiral structure (OB associations, HII regions, and cold interstellar HI gas), which are naturally fast evolving; dynamically, it is very active and responsive, because, being characterized by small random motions (a “cool disk”), it fuels Jeans instability. In contrast, the Population II disk, which is dynamically “warmer” because of the larger epicycles, contains the old stellar population betraying the underlying mass distribution - it is the ‘backbone’ of the galaxy (Lin 1971). One might expect – even in the absence of appreciable optical depths – for the two morphologies to be very different, since the near-infrared light comes predominantly from giant and supergiant stars (Rix and Rieke 1993; Frogel et al. 1996).

It is important to stress that from this physical (dynamical) point of view, one therefore requires two classification schemes – one for the Population I disk, and a separate one for the Population II disk. A near-infrared classification scheme can never replace an optical one, and vice-versa, because the current distribution of old stars strongly affects the current distribution of gas in the Population I disk. The dynamic interplay between the two components – via a feedback mechanism – is crucial, and has been studied extensively (eg. Bertin and Lin 1999, who term this mechanism a dynamical thermostat).

A central aspect here is the likely coupling of the Population I disk with that of the Population II disk via the feedback mechanism. To quote Pfenniger et al. 1996, “The interesting aspect of this coupling is that the systematic global properties of galaxies are then no longer necessarily determined by the initial conditions of collapse.”

We find a duality in spiral structure. A typical turbulent speed associated with the cold gas Population I component is ~ 6 km s⁻¹; in contrast, the velocity dispersion for old stars would typically be six times larger. While a gas cloud may be constrained to move in a thin annulus ∆r ~ 300 pc, an old star may wander in an annulus 2 kpc thick (Bertin and Lin 1996). To derive a coherent physical framework for the excitation of spiral structure in galaxies, one must consider the co-existence of the two dynamical components.

There is a fundamental limit in predicting what evolved stellar disks might look like. 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 there is a decoupling with a grand design old stellar disk. No prediction on that issue can, a priori, be made (Block, Elmegreen and Wainscoat 1996).

The theoretical framework to explain the co-existence of completely different morphologies within the same galaxy when it is studied optically and in the near-infrared is beautifully described by Bertin and Lin (1996), following the early pioneering work of Lindblad (1962). A global mode (Bertin et al. 1989a, 1989b) can be imagined as being composed of spiral wavetrains propagating radially in opposite directions, much like a standing wave. Thus a feedback of wavetrains is required from the center. The return of wavetrains back to the corotation circle is guaranteed by refraction, either by the bulge or because the inner disk is dynamically warmer. In the stellar disk, such a feedback can be interrupted by Inner Lindblad Resonance (ILR), which is a location where the stars meet the slower rotating density wave crests in resonance with their epicyclic frequency (Mark 1971, Lynden-Bell and Kalnajs 1972). In the gaseous disk, the related resonant absorption is only partial, so that some feedback is guaranteed. Once the above described wavecycle is set up (in the absence of a cutoff by ILR), a self-excited global mode can be generated.

The tightness of the arms in the modal theory comes from the mass distribution and rate of shear. Galaxies with more mass concentration, i.e., higher overall densities (including dark matter) and higher shear, should have more tightly wound arms.

If the disk is very light – low σ where σ is the disk density – the mode can be very tight, and one is in the domain of small epicycles (formally, the stability parameter Q = cκ/πGσ being close to unity, the value of c must
also be small. Here \( c \) is the radial velocity dispersion and \( \kappa \) is the epicyclic frequency).

If one increases the mass of the disk one finds a trend toward more open structures, but soon one runs the risk of a disk that is too heavy and a bar mode should manifest itself.

In those spirals with more open spiral arms at K but with no sign of a prominent bar, Bertin (1996) anticipates that the galaxy should be gas rich. Abundant gas can shock, dissipate and make some violently unstable open modes (see frame d of Fig. 4.5 in the book by Bertin and Lin 1996). This is one important reason why Bertin and Lin place ‘gas content’ in their theoretical framework for classification as the governing parameter for the trend from ‘a’ to ‘c’ galaxies (as indicated in Fig. 1 of Block et al. 1994).

The redistribution of angular momentum by large-scale spiral torques will be stronger for stellar arms which are more open; some authors (eg. Pfenniger et al. 1996) have postulated that such a redistribution may lead to rapid changes in the disk and even modify the properties of the rotation curve. This is the concept of secular evolution of a galaxy, from an open to a more tightly wound morphology, within one Hubble time.

Many galaxies show the presence of a significant \( m=1 \) component in the near-infrared (often in the form of a lopsidedness of the spiral). The linear modal theory predicts that \( m=1 \) modes should generally be dominated by \( m=2 \) modes when available, since the latter are more efficient than \( m=1 \) modes (see frame d of Fig. 4.5 in the book by Bertin and Lin 1996).

The near-infrared imaging of many of the spirals was secured at Mauna Kea and in Chile and fully described in Block et al. (1994a). At Mauna Kea, a Rockwell HgCdTe 256 \( \times \) 256 camera array was used, sensitive from 1 to 2.5 \( \mu m \). At the f:10 focus of the University of Hawaii’s 2.2m telescope, with 1:1 re-imaging optics, the scale is 0.37″/pixel, giving a field of 95″ \( \times \) 95″. At the European Southern Observatory at La Silla, we used the IRAC2 camera mounted on the ESO 2.2m telescope, in mode C (0.49″/pixel, giving a 2′ \( \times \) 2′ field of view). Both at La Silla and Mauna Kea, the K′ filter (2.1\( \mu m \)) was always selected. This filter is similar to K, but shifted 0.1 \( \mu m \) towards the blue, to reduce the thermal background (Wainscoat and Cowie 1992).

The K′ images of additional galaxies were very kindly made available to us by Dr P. Grosbøl (NGC 3223, NGC 5085, NGC 5247, NGC 5861 and NGC 7083), Dr M. Verheijen (NGC 3893, NGC 3938, NGC 3992 and NGC 4051) and Dr M. Thornley (NGC 3521 and NGC 5055).

The 2-D Fast Fourier decomposition of all the K′ images in this study, employed a program developed by Puerari (Schröder et al. 1994). In the decomposition, logarithmic spirals of the form \( r = r_0 \exp (-m \theta / p_{\text{max}}) \) are employed.

The amplitude of each Fourier component is given by (Schröder et al. 1994)

\[
A(m, p) = \frac{\sum_{i=1}^{I} \sum_{j=1}^{J} I_{ij} (\ln r, \theta) \exp (-i(m \theta + p \ln r))}{\sum_{i=1}^{I} \sum_{j=1}^{J} I_{ij}(\ln r, \theta)}
\]

where \( r \) and \( \theta \) are polar coordinates, \( I(\ln r, \theta) \) is the intensity at position \( \ln r, \theta \), \( m \) represents the number of arms or modes, and \( p \) is the variable associated with the pitch angle \( P \), defined by \( \tan P = -\frac{m}{p_{\text{max}}} \).

Our analytic Fourier spectra corroborate earlier observational indications (Block et al. 1994) that there is indeed an ubiquity of \( m=1 \) and \( m=2 \) modes, and that three principal archetypes for the evolved stellar disk of such galaxies may be proposed, based on the the pitch angle of the arms at K′ (see Figure 1). Figure 1 is generated from the actual deprojected images at K′ of our galaxies where the pitch angles have robustly been determined from the Fourier spectra. It is apparent that a galaxy with a winding angle at K′ of 18 degrees looks remarkably similar to one with a winding angle of 30 degrees (see Figure 1), and we classify those into one distinct bin. We choose to designate our three dust penetrated (DP) bins as \( \alpha, \beta \) and \( \gamma \), depending on the pitch angle of the dominant \( m \)-spiral at K′.

Those L=lopsided galaxies (where \( m=1 \) is a dominant mode) are designated Lo, L\( \beta \) and L\( \gamma \) according to the
Fig. 1. Logarithmic spirals with pitch angles determined from the Fourier spectra suggest three principal archetypes $\alpha$, $\beta$ and $\gamma$ for the classification of dust penetrated evolved Population II disks. Individual pitch angles are listed in Table 1.

Fig. 2. The Conselice symmetry number confirms that the disks of spiral galaxies are much more regular in the near-infrared, and therefore have a lower value at $K'$ compared to the value in the optical (B) regime.

is proposed that higher order modes (which may exist under special circumstances; see section 7 of this paper) be classified as $H_3$ (for $m=3$) and $H_4$ (for $m=4$), followed by a class description $\alpha$, $\beta$ or $\gamma$ appropriate to the pitch angle of the stellar arms.

The terminology DP highlights the fact that at $K'$, one is looking at dust penetrated images. It is dust in the gaseous Population I disk which so often obscures the underlying Population II disk. It is because of dust that a galaxy can masquerade as late type c (for the optical morphology) but as early type a in the dust penetrated Population II regime (Block and Wainscoat 1991). It is dust which obscures the regular two-armed spiral structure found in many optically flocculent galaxies (eg. Grosbøl and Patsis 1996, 1998, Thornley 1996). Optical images, combined with near-infrared ones, together with the use of radiative transfer models highlight the fact that gaseous Population I disks often have optical depths $\tau(V) \sim 1$ and more (Block et al. 1994b, Elmegreen and Block 1998) which is why there can be no prediction of what an evolved stellar disk of a optically flocculent galaxy, for example, might look like (Block, Elmegreen and Wainscoat 1996).

We have avoided using I, II or III for our dust penetrated classes and have used $\alpha$, $\beta$ and $\gamma$ instead, to prevent confusion with the optical luminosity classification scheme of galaxies (van den Bergh 1960).
While there may appear to be a resemblance of our groups to the Hubble bins in terms of the openness or pitch angle of the arms, there is no similarity whatever. It is possible for a late type Sc galaxy (eg. NGC 5861 below) to have a stellar disk with tightly wound arms with a pitch angle at $K'$ of $13^\circ$, which demarcates it to our tightly wound group $\alpha$ class. Conversely, it is possible for two galaxies on opposite ends of the Hubble sequence (a, c) to both have evolved disks of dust penetrated group $\beta$: NGC 718 and NGC 2997 are examples which both belong to group $\beta$, but have Hubble classifications of a and c respectively. (The near-infrared pitch angles of NGC 718 and NGC 2997 differ by only 1° – see Table 1.) It is also possible for an optical irregular to have smooth stellar spiral arms with a well-defined pitch angle at $K'$ and to belong to one of these groups (eg. the companion to M51, as discussed below).

The range of radii over which the fit was applied are all listed in Table 1. These were selected to exclude the bulge (where there is no information on the arms) and extend to the outer limits of the arms in our images. It is important to discuss the error bars on the determination of our pitch angles using Fourier transform techniques. We use a Fast Fourier Transform, where the incremental step-size in the spectrum is $\Delta p$. We calculate the spectrum from $-50 < p < 50$ and select a step-size of $\Delta p=0.25$.

Table 1. Optical Hubble type, dust penetrated (DP) morphologies, near-infrared pitch angles and radial range of fit.

| GALAXY  | DP Class | Morph. Type | $P_K'$ | Range of fit |
|---------|----------|-------------|--------|--------------|
| NGC 2841 | E$\alpha$ | Sb | 9° | 70°, 165° |
| NGC 3223 | E$\alpha$ | Sb | 9° | 15°, 48° |
| NGC 3521 | E$\alpha$ | Sbc | 14° | 12°, 157° |
| NGC 3992 | E$\alpha$ | SBC | 11° | 61°, 184° |
| NGC 4622 | E$\alpha$/L$\alpha$ | Sb | 8° | 11°, 50° |
| NGC 5055 | E$\alpha$ | Sbc | 13° | 18°, 150° |
| NGC 5861 | E$\alpha$ | Sc | 13° | 17°, 50° |

Group $\beta$

| NGC 309 | E$\beta$ | Sc | 18° | 11°, 44° |
| NGC 718 | E$\beta$ | Sa | 24° | 11°, 34° |
| NGC 1637 | E$\beta$/L$\gamma$ | Sc | 30° | 13°, 45° |
| NGC 2997 | E$\beta$ | Sc | 25° | 34°, 122° |
| NGC 3893 | E$\beta$ | Sc | 21° | 12°, 88° |
| NGC 3938 | E$\beta$ | Sc | 22° | 12°, 168° |
| NGC 4736 | E$\beta$ | Sab | 28° | 37°, 56° |
| NGC 5247 | E$\beta$ | Sc | 30° | 30°, 90° |

Group $\gamma$

| NGC 4051 | E$\gamma$ | SBC | 49° | 16°, 180° |
| NGC 5085 | E$\gamma$ | Sc | 39° | 25°, 50° |
| NGC 5195 | E$\gamma$ | Irr | 49° | 26°, 52° |
| NGC 7083 | E$\gamma$ | Sb | 36° | 15°, 40° |

The error bars decrease with the degree of tightness of the arm pattern. In NGC 5195 for example – with very open stellar arms – the spectrum peak occurs at $p=1.75$ (see Figure 7). We therefore compute a pitch angle in Table 1 of $P=atan(m=2/p=1.75)=48.8^\circ$. If the peak was to occur one step-size later, at $p=2.0$, the computed pitch angle would have been $P=45.0^\circ$. If the Fourier spectrum was to have peaked at $p=1.5$, one step-size earlier, then $P=53.1^\circ$. So, for this galaxy, our pitch angle at $K'$ of $P=48.8^\circ$ has an error bar of $(-4.3, -3.8)$ degrees.

On the other hand, let us consider NGC 3992, with its tightly wound arms. The Fourier spectrum peaks at $p=10.25$ (see Figure 3), and so the derived pitch angle in Table 1 is $P=11.0^\circ$. If the peak were to have occurred at $p=10.0$, the pitch angle would have been $P=11.3^\circ$. If the spectrum peaked one step-size later at $p=10.5$, the derived pitch angle would be $P=10.8^\circ$. In this case, the error bar for our listed $11^\circ$ tightly wound arm structure in NGC 3992 is (+0.3, −0.2) degrees.

In the tightly wound scenario, it is perhaps not too meaningful to quote error bars on the pitch angle of only $\sim \pm0.2^\circ$. Spirals with $P=11.0^\circ$ or $P=11.2^\circ$ will only be ‘different’ after a number of winding angles or turns, and we know it is difficult to find arms at $K'$ which actually wind round more than $360^\circ$, although such galaxies do exist (eg. Fig 6b in Block et al. [1994]).

Pitch angles can either be determined from the peaks in the Fourier spectra (as above), or from the slopes in $(ln(r), \theta)$ plots, where logarithmic spirals appear as straight lines. In both cases, careful deprojections to face-on are critical. Our experience with estimating pitch angles from $(ln(r), \theta)$ plots is that eyeball identification of the straight lines (arms) and of their resulting slopes can be very difficult, especially if the arm/interarm contrast in the near-infrared image is not high. On the other hand, peaks in Fourier spectra are unambiguous.

As other authors have advocated in the past (eg. Considère and Athanassoula [1988], García-Gómez and Athanassoula [1993]), the Fourier transform is the most powerful method to find periodicity in a distribution, whether it be one dimensional (such as radial stellar pulsations) or bi-dimensional (as for the spiral arms in an image). That there are galaxies with very open arm morphologies, with pitch angles as large as $37^\circ$, is corroborated by these earlier studies. For example, Considère and Athanassoula [1988] analysed blue (B) images of 16 galaxies, and found pitch angles as large as $37^\circ$. García-Gómez and Athanassoula [1993] determined pitch angles of $43^\circ$ for NGC 5194 and $55^\circ$ for both NGC 3627 and NGC 7741. Many other examples are provided in their table. These large pitch angles were only for the main m=2 component; García-Gómez and Athanassoula
posed by Conselice (1997) for each of our B and K’ components which they see in their spectra.

We have also computed the symmetry number proposed by Conselice (1997) for each of our B and K’ images:

\[ C^2 = \frac{\sum I_0 - I_{1380}}{\sum I_0} \]

The number is determined by rotating every image through 180° about the centre, subtracting that from the original image and normalising. We did this to illustrate that highly symmetric evolved disks exist for all three of our dust penetrated groups (see Figure 2). A value of \( C_\lambda = 0 \) corresponds to a completely symmetric galaxy at wavelength \( \lambda \); for a completely asymmetric galaxy, the ratio is unity.

In contrast to the work of Conselice, where a homogeneous sample was used, our sample here is drawn from a non-homogeneous one (different instruments and different observers). Care must be exercised when working with images from different instruments: the potential problem is that of noise – especially in the near-infrared, where disk features might be of a low contrast and where the sky is bright. A greater dispersion can be expected, but the quantitative trend observed in Figure 2 confirms our earlier qualitative findings in Block et al. (1994a), that disks at K’ are much more regular and symmetric than seen at shorter wavelengths, such as B.

The Conselice number does not increase with dust penetrated class. For example, its value for NGC 5195 is only 0.031 at K’, confirming the visual impression of a very symmetric evolved disk (see Fig. 5b in Block et al. 1994a). While the Conselice method might be used to confirm the presence of symmetric disks in all three of our dust penetrated archetypes, it is the pitch angle of the arms at K’ which determines to which dust penetrated bin a galaxy should be assigned.

3. Dust penetrated group \( \alpha \)

Our Fourier spectra of these galaxies, with tightly wound stellar arms at K’, are illustrated in Figures 3 and 4.

NGC 3223 is an optically multi-armed specimen of Hubble type Sb and van den Bergh (1966) luminosity class I-II. In the near-infrared, however, this galaxy shows two bright, grand design stellar density waves (SDWs) (see Grosbøl and Patsis 1996, 1998). That multi-arm galaxies such as NGC 3223 may present long, continuous arms with well-defined pitch angles at K’ is not uncommon: for the famous optically flocculent prototype NGC 2841 (Elmegreen arm class 3 = ‘fragmented arms uniformly distributed around the galactic center’; see Elmegreen and Elmegreen 1987), a remarkable system of four long and regular spirals at K’ is reported (see Block, Elmegreen and Wainscoat 1996 and Block 1996). Independent studies by Grosbøl and Patsis (1998) and Thornley (1996) show that NGC 2841 is no exception: many optically flocculent galaxies reveal a regular two-armed spiral structure in the near-infrared.

These include NGC 5055 and NGC 3521 (Thornley 1996). Both NGC 5055 and NGC 3521 are of Elmegreen arm class 3, but the spiral arms of these two optically flocculent galaxies with ‘grand design’ m=2 near-infrared counterparts have a pitch angle at K’ of 13° and 14° respectively, and both galaxies are assigned to our dust penetrated \( \alpha \) bin.

If, in the midst of stellar density waves (SDWs), SDW pressures are less than the average turbulent gas pressure, the competition between stars and gas is won by gas: the galaxy would present an optically fragmented, flocculent appearance (Block 1996). The star formation history, principally triggered from previous bursts of star formation (rather than SDW pressures), would be stochastic/random. High total gas column densities (and therefore relatively large optical depths at B or V) would be predicted. Indeed, the V optical depth in NGC 3223 is \( \sim 2 \) at certain radii (see Block 1996) and it is dust which hides the m=2 near-infrared spirals.

We next turn our attention to NGC 5861 and NGC 3992. Both are described by Sandage and Bedke (1994) as having spiral patterns which rank amongst ‘the most regular in the sky’. They are exquisite grand design galaxies which pitch angles at K’ of 13° and 11° respectively, and both galaxies are assigned to our dust penetrated \( \alpha \) bin.

It is therefore particularly important to note that the evolved stellar disks of some of the most exquisite grand design galaxies may belong to the same dust penetrated class as those of the best known optically flocculent prototypes. Indeed, NGC 5861 is of Elmegreen class 12 (defined in Elmegreen and Elmegreen 1987 as having ‘two long symmetric arms dominating the optical disk’) while NGC 5055 and NGC 3521 are of Elmegreen arm class 3 – almost as optically flocculent as one can find.

NGC 4622 is an Sb galaxy which displays dual spiral structure (Byrd et al. 1988). Both the outer pair and the inner arm reveal amplitude modulation. The inner arm is probably the first confirmed evidence for a leading spiral arm. Based on the sequential structure of the BVI photometry of the leading arm, beautiful evidence has been given (Buta, Crocker and Byrd 1992) in support of the pattern being a counter–rotating density wave. A method to determine the arm character (trailing or leading) in spiral galaxies using the Fourier analysis of azimuthal profiles is presented by Puerari and Dottori (1997).

Our Fourier decomposition of the K’ image of NGC 4622 confirms a strong m=1 mode which is identified with the inner (leading) arm. The pitch angle at K’ for that m=1 arm is only 4°. In Block et al. (1994a), we argued that the leading arm of NGC 4622 is truly exceptional and requires external driving (much like a damped mode of a church bell), because the torques associated with leading structures are unfavorable to self–excitation. The rarity
Fig. 3. The Fourier spectra for our group α galaxies. Although the dominant mode is $m=2$, note that some galaxies (eg. NGC 3233, NGC 3521 and NGC 3992) have significant higher order $[m=4]$ modes at $K'$. The single leading arm of NGC 4622 has a striking $m=1$ component at $K'$.

of leading arms among grand design galaxies may be an indication that tidal driving is very seldom efficient. The pair of magnificent $m=2$ arms winding in the opposite direction have a pitch angle at $K'$ of $8^\circ$, and the galaxy is assigned to our dust penetrated α bin.

We had earlier published a plot of log(radius) versus azimuthal angle for our $K'$ image of NGC 2841, where the long arms appear as straight lines (see colour Plate 2b in Block [199]). The pitch angle of the spiral arms can easily be read off from the slopes of the tilted features;
Classification of dust penetrated disks

Fig. 4. The Fourier spectra of additional galaxies in our dust penetrated $\alpha$ group shows an ubiquity of $m=1$ and $m=2$ modes.

they are found to be approximately $9^\circ$. The tightly wound arms at $K'$ of this prototypically flocculent specimen at optical wavelengths suggests that we place it in our dust penetrated $\alpha$ classification.

Although all the galaxies in Figures 3 and 4 show Fourier spectra where the most dominant mode is $m=2$ so that they all belong to the two-armed, evensided $E\alpha$ group, there is nevertheless an ubiquity of the lower-order $m=1$ mode as well. The only exception where $m=1$ is as dominant as $m=2$ is NGC 4622, which we have already noted has one presumably leading arm ($m=1$) and a pair of outer (presumably trailing) $m=2$ arms. Note, too, the presence of higher order [$m=4$] modes, but with considerably lower amplitude than the $m=2$ mode, in galaxies such as NGC 3223, NGC 3521 and NGC 3992.

4. Dust penetrated group $\beta$

The Fourier spectra of these galaxies are presented in Figures 5 and 6. Galaxies with a very large range in optical morphology – from Sa to Sc – are to be found in this dust penetrated class. They also span a very wide range of Elmegreen arm class in the optical; from extreme grand design arm class 12 to flocculent arm class 3.

We firstly turn our attention to the Sc galaxy NGC 309, of luminosity classification I (van den Bergh 1960). We have already noted that this galaxy has some of the linearly widest Population I arms known (Block 1982). Optically, NGC 309 presents a multi–armed morphology (see Block and Wainscoat 1991 and the Elmegreen arm class is 9 (‘two symmetric inner arms; multiple long and continuous outer arms’ as defined by Elmegreen and Elmegreen 1987). However, at $K'$ it looks like an SBa galaxy, betraying (1) a prominent bar and (2) two symmetrical arms only, with winding angle just over $180^\circ$ and a pitch angle of $\sim 18^\circ$. The surface brightness enhancements of the $m=2$ stellar components at $K'$ are approximately 60 % above that of the underlying disk. Normal (ScI) and barred (SBa) large scale structures co–exist within the same galaxy.

Next, we focus our attention on another galaxy whose evolved disk is very similar to that of NGC 309: NGC 718. NGC 718 is optically classified as SaI, but its evolved disk belongs to the same group at that for NGC 309. The pitch angle of its two spiral arms at $K'$ is $24^\circ$ and we assign it to our dust penetrated $\beta$ bin.

Another galaxy which belongs to the same dust penetrated class as NGC 309, is the early type spiral NGC 4736. NGC 4736 is classified as type RSab(s) and is of Elmegreen optical arm class 3. The galaxy is famous for its inner, ‘knotty ring’ of HII regions (see Figure 8 in Block et al. 1994a). Our $K'$ image reveals a pair of logarithmic spiral arms, with a pitch angle at $K'$ of $28^\circ$. The galaxy is assigned to the dust penetrated $\beta$ bin.

Also in this dust penetrated class is the grand–design Sc(s)I spiral NGC 2997 (Sandage and Tammann 1987).
Optically, the galaxy possesses two dominant spiral arms, one of which has a prominent western branching into a third arm (see Block et al. [1994]). NGC 2997 is of Elmegreen arm class 9. At K′ the galaxy reveals a small oval distortion and a distinct m=1 component. The most natural interpretation is that there are two dominant modes, m=1 and m=2, with negative interference on the northern side. The pitch angle of the stellar arms at K′ is determined to be ∼25° and we assign NGC 2997 to our dust penetrated β bin.

Not only are Sa to Sc galaxies all to be found in this dust penetrated class, but the dust penetrated β bin again spans almost the entire range of optical Elmegreen arm classes: from extreme grand design arm class 12 (e.g. NGC 718) to flocculent arm class 3 (e.g. NGC 4736).

From our Fourier spectra for these class β Population II disks, we note that although the dominant mode is m=2, there is an ubiquity of m=1 modes as well, with lower amplitude. The m=1 component is nearly as striking as the m=2 component in some of the galaxies such as NGC 3893 and NGC 3938 (Figure 6) while m=1 has a much lower amplitude than m=2 in others, such as NGC 5247. Higher order modes (also with lower amplitude than m=2) are also to be found: NGC 2997 shows a distinct m=3 component at K′, while NGC 309 and NGC 1637 reveal significant m=4 modes in the near-infrared (Figure 5).

5. Dust penetrated group γ

The Fourier spectra for these galaxies are presented in Figure 7.

We firstly turn our attention to NGC 5195, the companion of NGC 5194 = M51. Optically, NGC 5195 has been classified as Ip-Ep (Morgan 1958), Irr II (Sandage 1961), Sb(r) (Spinrad and Harlan 1972) and SB0/a(r) (Thronson, Rubin and Ksir 1991). Our K′ image, radically different from the optical, shows no evidence for tidal disruption of its old stellar population disk by M51 (Figure 5b in Block et al. [1994]). The striking symmetry in the NGC 5195 Population II disk (see the K′ image in Fig. 5b in Block et al. [1994]) and confirmed by the evensided Fourier mode m=2 in Figure 7 of this paper) is confirmed by a low Conselice number at K′.

The bisymmetric structures look more like intrinsic global modes where the m=2 spirals have a pitch angle at K′ of 49°. In view of the exceptional symmetry at K′, NGC 5195 is likely to have just disturbed M51’s spiral arms (Oort 1970). The tidal interaction here is far less dramatic than usually thought, based on the more prominent features of the lighter Population I disks. As suggested by Block et al. [1994], the prominent isophotal twisting within the bar itself may be the quantitative signature of the tidal field of M51 on the intrinsic bar structure of NGC 5195. Isophotal twisting of the central bar regions is not uncommon (Shaw et al. 1993) and might be simply due to the incipient spiral structure, commencing with a sharp turn at the bar tip, as often found for intrinsic modes (see the discussion of NGC 1300 in Bertin 1993 or Fig. 10 of Benedict et al. 1992 for NGC 4314).

Members of this dust penetrated γ group include an early type spiral (NGC 7083), a late type spiral (NGC 5085) as well as an optical irregular. NGC 5085 is of Elmegreen arm class 2 (‘fragmented spiral arm pieces with no regular pattern’). Also included is NGC 4051, of Elmegreen arm class 5 (‘two symmetric short arms in the inner regions; irregular outer arms’).

The Fourier spectra for dust penetrated group γ galaxies with open stellar arms in Figure 7 show that the dominant Fourier mode is m=2. However, modes of higher order do exist (e.g. m=4 for NGC 5085).

6. Classifying lopsided galaxies

NGC 1637, for example, draws attention because of its exceptional lopsidedness, with a somewhat squarish shape, although there is a regular bisymmetric spiral close to the nucleus. It is classified as Sc (Sandage 1961), but shows a marked lopsidedness (an m=1 feature) in the old Population II disk (see Figure 9b in Block et al. [1994]).

If one wishes to draw attention to lopsidedness in galaxies displaying a prominent m=1 feature, we propose that the galaxy still be placed in the α, β or γ bin, according to the pitch angle of the m=1 component, but that a prefix L clearly be used to designate the lopsidedness in the evolved disk. The m=1 feature itself may be prominent, but not dominant, as in NGC 1637.

We have carefully examined the m=1 feature at K′ of NGC 1637 in a (lnR, θ) diagram and find a straight line, indicating that the fit of a logarithmic spiral to that m=1 arm is excellent. From the slope, we find the pitch angle of the m=1 arm to be ∼35°.

We have analysed the inner bisymmetric spiral by setting an appropriate annulus to encompass the inner spiral but exclude the outer m=1 arm. The spiral shows up clearly at K′ in the spectra, and the pitch angle of the dominant m=2 component (Figure 5) is 29°. For the regular m=2 bisymmetric spiral, a dust penetrated Eβ would be appropriate.

Binning according to the asymmetric/lopsided mode of m=1 here, the m=1 spiral belongs to the dust penetrated γ bin and would be designated Lγ. The pitch angle of the lopsided m=1 arm is 6° greater than for the m=2 mode. In Figure 1, NGC 1637 is included by plotting an m=1 logarithmic spiral with a pitch angle of 35°.

No companion for NGC 1637 is found on the Palomar Observatory Sky Survey within one degree. Such extreme lopsidedness could be a general feature in some isolated galaxies, for which the persistence of such m=1 asymmetries (Baldwin, Lynden-Bell and Sancisi 1980) should be explained. As exemplified by these authors, lopsided prototype galaxies such as NGC 891 and 5457, are in-
Indeed, a lopsidedness both in the light and in the neutral HI gas. Within the modal theory, one may argue that lopsidedness and one-armed structures are all non-linear m=1 modes. In the linear theory they may be the m=1 equivalent of what is more commonly noted as barred and normal two-armed spiral modes (the former occurring in heavy, fully self-gravitating disks and the latter occurring instead in light disks). If this is so, such an extreme lopsidedness in the stellar disk would be more natural if the disk is heavy. Indeed, a prominent bar is observed in the old stellar disk of NGC 1637.

7. Higher order harmonics

While there is an ubiquity of m=1 and m=2 modes in our sample (Figures 3–7), higher order modes in some instances do exist, as we have already pointed out. However, in no galaxies in our sample are the higher order modes the dominant ones.

In the K-band study of 45 spirals by Seigar and James (1998), the most common dominant modes were also found to be the lopsided L (m=1) and evensided E (m=2) – each of which was found to arise in their sample in about 1/3 of the galaxies.

The sample of Seigar and James (1998) showed a great dearth of spirals with dominant m=3 (only 4 out of the 45 cases), but nevertheless such galaxies do exist and one must be able to classify them in a dust penetrated regime. Seigar and James (1998) did find that approximately 25% of their total showed a dominant m=4 mode in the K-band.

We would suggest the terminology H3 and H4 for the third and fourth harmonics, to assist with easy visualisation of their evolved disk morphologies.

Can modes greater than m=2 develop within the modal theory of spiral structure? Already in the paper by Block et al. (1994) and by Bertin (1996) it was hinted that:

Firstly, in a gas-rich system some higher-m modes should develop, and that might also induce some response in the stellar disk, for the stronger cases.

Secondly, non-linearly modes may couple and again give rise to higher-m structures 2 + 1 = 3 and 2 + 2 = 4 (Block et al. 1994 and Bertin, private communication). A variation on this theme is the following: if one takes a strong bisymmetric bar and Fourier-analyze the deprojected image, one may indeed find m=4 and even m=6 to be prominent, even when one does not see actually four or six arms. If the bar is strong enough to drive the disk, an m=4 response in the outer disk may show up. It is interesting to note that almost all of the m=4 cases cited by Seigar and James (1998) are classified as barred in the optical.

Thirdly: another point to consider for the generation of higher-m modes is the underlying rotation curve. If the shear is very mild (some Sc’s have a large part of their disks in almost solid body rotation), then the ILR is less effective (Bertin, private communication) and m=3 and even m=4 modes might develop.

We suggest that these H3 and H4 galaxies, too, should be binned in the dust penetrated regime, according to the pitch angle of their stellar arms.

All of the H3 and H4 galaxies in Seigar and James (1998) belong to our dust penetrated α class, so that a galaxy such as UGC 2303 (m=3, with a pitch angle at K of 45°) would be classified here as H3α, while a spiral such as IC 357 (m=4, with a K pitch angle of 85°) is classified here as H4α.

8. Inverse Fourier Transform analysis

In Figure 8, we present the inverse Fourier transforms of six of the galaxies in Table 1, two from each α, β and γ dust penetrated classes.

After having deprojected the K' images and identifying the dominant modes, we next calculated the inverse Fourier transform, as follows:

We define the variable $u \equiv \ln r$. Then

$$S(u, \theta) = \sum_m S_m(u) e^{i m \theta}$$

where

$$S_m(u) = \frac{D}{e^{2 u n} 4 \pi^2} \int_{-\infty}^{+\infty} G_m(p) A(p, m) e^{i p u} \, dp$$

and

$$D = \Sigma_i I_i(u)$$

$G_m(p)$ is a high frequency filter used by Puerari and Dottori (1992). For the spiral with

$$\tan P = -\frac{m}{p_{\text{max}}^m}$$

it has the form

$$G_m(p) = \exp\left[ -\frac{1}{2} \left( \frac{p - p_{\text{max}}^m}{25} \right)^2 \right]$$

where $p_{\text{max}}^m$ is the value of $p$ for which the amplitude of the Fourier coefficients for a given $m$ is maximum. This filter is also used to smooth the $A(p, m)$ spectra at the interval ends (see Puerari and Dottori 1992).

The contour overlays of the inverse Fourier transforms in Figure 8 indicate the excellent fit of our pitch angles, robustly derived from the Fourier spectra. In the top panel of Figure 8, two galaxies with tightly wound pitch angles at K', belonging to the α class, are presented. The galaxies are NGC 3223 (optical Hubble type b) and NGC 5861 (optical Hubble type c). The fit of logarithmic spirals to the arms is excellent (Figure 8), as was already alluded to by the pioneering empirical rectifications of logarithmic spirals by Danver (1942). In the middle panel of Figure 8, two galaxies (NGC 718 and NGC 309) are presented;
they belong to class $\beta$; again the overlay of the inverse Fourier transform confirms the robustness of the Fourier technique of identifying the dominant mode and binning according to pitch angle at $K'$. Note that NGC 718 is of Hubble type a, while NGC 309 is of Hubble type c. Finally, contour overlays of the Fourier transform for two of the class $\gamma$ spirals (NGC 5085 – Hubble type c and NGC 7083 – Hubble type b) are illustrated in the lower panel of Figure 8.

9. Discussion

The question of whether star formation actually traces underlying spiral structure in the Population II disk – in other words, whether spiral density waves actually trigger star formation – has been elegantly reviewed by Elmegreen (1995). The issue is whether the interstellar gas does not form many stars while it is in the interarm regions, but rapidly forms stars when it enters a stellar spiral arm.

Since an optically flocculent galaxy can belong to the same dust penetrated bin as that of an optically grand design and both have a dominant $m=2$ mode in the near-infrared, the implication is that stellar density waves do not principally trigger star formation – for if they always did, the morphology of the optical disk would closely mimic its dust penetrated archetype. Only if star formation traced density waves could one predict what the underlying mass distribution of a galaxy would be and what the dust penetrated class would be, which one cannot. NGC 3521 has a regular two-armed stellar mass distribution; in the optical, this galaxy is flocculent.

Important confirmations of this result are to be found in the literature. Elmegreen and Elmegreen (1986) showed that the star formation rate per unit area, from UV, FIR, H$\alpha$, integrated colour, and surface brightness data, is the same for grand design and flocculent galaxies. A study by McCall and Schmidt (1986) showed that the fraction of galaxies with grand design spirals is the same whether they have Type I, Type II, or indeed no recorded supernovae, which implies that this fraction is independent of the supernova rate.

Similar inferences have been made for our Galaxy. Talbot (1985) found that the star formation rate per unit molecular mass in the Milky Way is independent of radius, and Wouterloot, Brand and Henkel (1988) found the same star formation rate per unit molecular mass for molecular clouds in the far-outter disk of our Galaxy.

Viewed at arcsecond resolution, it has become clear that interarm dust (and gas) can be very widespread, covering much of the optical disk of a spiral galaxy (eg. Block 1996). Giant molecular associations are to be found in flocculent as well as grand design spirals (eg. Sakamoto 1996). A unified view of macromolecules, very small grains and large dust particles in the Whirlpool Galaxy M51 has recently been produced by combining optical and Infrared Space Observatory data (see Block et al. 1997). Widespread spirals of macromolecules and dust grains lie not only in the arm, but also in the interarm regions (see Figure 1 in Block et al. 1997). If these spirals are indeed precursors to density wave triggered star formation, a partial decoupling of the Population I and II disk is suggested (the reader is referred to the ‘smooth red arums’ and ‘bar’ in the Population II disk of M51 shown by the photographic work of Zwicky (1957).

Finally, there are indications from rotation curve analyses that optical Hubble type is not correlated with the evolved Population II morphology. Indications are that the distribution of stellar mass in the disk, to which the properties of rotation curves are tied, can be different for the same Hubble type (see Burstein and Rubin 1985). These authors find three principal types of mass distribution, with Hubble type a and b classes being found among all three types more or less equally. To secure rotation curves, one selects galaxies from a sample which are well inclined to the line-of-sight; whereas for morphology, a preferentially face-on criterion is essential to delineate and study the arms. If the arms could clearly be delineated in their sample of (inclined) galaxies, it would not be unreasonable to predict that a correlation might be found between our dust penetrated classes and their three principal types of mass distribution.

10. Conclusions

To derive a coherent physical framework for the excitation of spiral structure in galaxies, one must consider the co-existence of two different dynamical components: a gas-dominated Population I disk (OB associations, HII regions, cold interstellar HI gas) and an evolved stellar Population II component. The Hubble classification scheme has as its focus, the morphology of the Population I component only.

Our first major conclusion of this observational study is that there is an ubiquity of $m=1$ and $m=2$ modes in the near-infrared regime (Figures 3–7).

Secondly, three principal archetypes $\alpha$, $\beta$ and $\gamma$ for the dust penetrated morphology may be proposed, characterised by pitch angles at $K'$ of $\sim 10^{\circ}$ (the $\alpha$ class), $\sim 25^{\circ}$ (the $\beta$ class) and $\sim 40^{\circ}$ (the $\gamma$ bin), respectively (see Figure 1).

The ubiquity of low- $m$ features finds a natural interpretation within the modal theory, because higher- $m$ modes are expected to be damped by absorption at the ILR in the evolved stellar disk. If the shear in a galactic disk is not high, it is possible for higher- $m$ modes to develop as the ILR is then not as effective. Such higher- $m$ modes may also develop for gas-rich galactic disks.

Thirdly, the dynamical behaviour of gas and young OB stars is often decoupled or partially decoupled from that of Population II disk, and this explains why an Sc can mimic an SBa at 2.1$\mu$m.
Optically flocculent galaxies of arm class 3 can have almost identical evolved disk morphologies to those belonging to optically grand design spirals of arm class 12.

Fourthly, and related to the decoupling: we find no correlation between optical Elmegreen arm class and pitch angle in the dust penetrated regime (see Table 1). In the $\beta$ bin, the variation in Elmegreen arm class in Table 1 is again from flocculent (3) to grand design (12). Figure 9 clearly shows why a completely new classification of disks in the near-infrared domain is called for: two galaxies having completely different Elmegreen arm classes can have almost identical pitch angles at $K'$. In Figure 10, we plot a similar graph, but of pitch angle at $K'$ versus de Vaucouleurs’ T index. The $\alpha$ dust penetrated archetype can be the resident disk to a vast range of optical Hubble or de Vaucouleurs’ T indices. Likewise for the $\beta$ and $\gamma$ classes.

Although the $m=2$ mode is a dominant mode in our Fourier spectra (Figs. 3–7), there is often a significant $m=1$ component as well. If one wishes to draw attention to the $m=1$ mode, we have proposed that a prefix L indicate the lopsidedness; the dust penetrated classes would then be $L\alpha$, $L\beta$ and $L\gamma$. Any of the $L$ archetypes will look like one logarithmic spiral (instead of two) in Figure 1, determined by the appropriate pitch angle. In that Figure, we have plotted one logarithmic spiral for the $m=1$ mode of NGC 1637 and for the (leading) arm in NGC 4622. We use the terminology $E=$evensided for dominant two-armed ($m=2$) modes, and $H3$ and $H4$ for third and fourth order harmonics.

Among the $m=2$ modes, it may also be appropriate, in due course, to introduce a class $F=$fragmentary, for stellar disks which are patchy and irregular. It is important that the letter $I=$irregular not be used, since a few optically flocculent and late type Sd spiral galaxies, for example, can belong to this group. An example of an F class would be the flocculent type Sd companion to M81, NGC 2976 (see section 1.3 in Block 1994), which presents a very irregular appearance in the near-infrared – no central mass concentration and no coherent stellar morphology at all.

As in the optical scenario, it cannot be expected of any classification scheme to include every single galaxy. The cosmic tapestry, especially at high $z$, is too rich and varied. There is one additional crucial point pertaining to galaxy morphology classification in the high redshift Universe: the detection of an ‘old’ stellar disk (ages greater than 1 or 2 Gyr) beyond a redshift of 1.5 is extraordinarily difficult – see Figure 6 in Abraham (1998). As one probes progressively deeper into redshift space, the rest frame of a galaxy systematically shifts to the ultraviolet. This is the morphological K-correction: one is observing galaxies at bluer rest wavelengths as a function of redshift. Strong surface brightness selection effects bias against the detection of even intermediate-aged stellar populations (see Abraham 1998) and the decline in visibility of older stellar populations with redshift is dramatic. The late type/’irregulars’ reported in many of the higher redshift galaxies in the Hubble Deep Field (HDF) describe ultraviolet morphologies of the gaseous disks only. Some of these disks could possibly be partially or fully decoupled from their stellar disks as we find locally for the optical irregular in the system NGC 5195/M51. (A promising note is that Fourier

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Note: A short aside: Four of the galaxies in our sample do not have listed Elmegreen arm classes, as they were not included in the sample of Elmegreen and Elmegreen (1987).
decompositions can be done on HDF images. This is provided that the number of components used in the decomposition is not too large (Windhorst, private communication) since faint galaxy images are so small, even with the Hubble Space Telescope).

Returning to the F class: while some optical irregulars may belong to this type, the dust penetrated disks of other optical irregulars (eg. NGC 5195) would not. We believe that while modes have been identified in large ensembles of dust penetrated galactic disks in our local low redshift Universe, there of course will always be exceptions where there are no indications of any spiral arms or of modes – NGC 2976 is one example.

We have deliberately kept our preliminary dust penetrated classification scheme simple. Of course it is possible to use the terminology (B)Eα, (B)Eβ and (B)Eγ for example, to indicate the presence of a bar in the evolved disk of evensided galaxies – and possibly to give a measure of bar strength in terms of the ‘equivalent angle’ of Seigar and James (1998a, see their Figure 10). However, since it is not uncommon for a barred and unbarred morphology to co-exist within the same galaxy, we have only differentiated evolved disks here on the basis of the dominant Fourier mode and on the opening or pitch angle of the stellar arms. It is a starting point. The caution of Mike Disney (1996) rings in our ears:

“What would worry me is that everybody will go off now and write their own morphology and we’ll have 500 more different K-band morphological categories. I don’t know how to solve it; perhaps several people at this conference should go away and agree to do it. At least to have some starting places for it – otherwise it may be as haphazard as it’s been in the past in the optical.”

In this paper, we have tried to stress the fundamental rather than incidental need to develop a near-infrared classification scheme of galaxies. Up to now, we have only classified one of the two components: the Population I disk. A central aspect here is the likely coupling of the Population I disk with that of the Population II disk via a feedback mechanism.

Having formulated our dust penetrated classification scheme above, we have tested it on an independent sample of 45 face-on galaxies observed in the K-band by Seigar and James (1998a). It is interesting to note that Seigar and James did not study galaxies with very open arm morphologies in the near-infrared. Indeed, 44 out of their 45 galaxies have pitch angles at K less than 13°, which designate them to our α bin. Nevertheless, this strengthens our conclusion even further, that one specific dust penetrated archetype (in this instance, class α) may be the resident disk to a further 44 spirals with a wide range in optical morphologies: from early (α) to late type (d) in their Table 1.

It is perhaps important to reflect back to the thoughts of Hubble (1936) in deciding which features should be included, and which features should be excluded, when classifying galaxies:

“The features must be significant – they must indicate physical properties of the nebulae [galaxies] themselves and not chance effects of orientation – and also they must be conspicuous enough to be seen in large numbers of nebulae.”

We see a duality of spiral structure. One for the Population I disk; often a radically different one for the Population II disk. One half of the story has been missing. A feedback between a young Population I disk of an optically flocculent galaxy, and an old grand design Population II disk, for example.

Finally, the morphology of evolved disks with open stellar arms could be interpreted as favouring the secular evolution of galaxies – from an open to a more tightly wound scenario: the redistribution of angular momentum by large-scale spiral torques being more efficient for those stellar arms which are more open (eg. Pfenniger et al. 1989). Combes and Sellwood, private communications).

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References

Abraham, R.G., 1998, Les Houches preprint, astro-ph 9809131
Allen, R.J., 1996, in New Extragalactic Perspectives in the New South Africa, eds. D.L. Block, J.M. Greenberg, Kluwer, Dordrecht, p. 608
Baade, W., 1963, Evolution of Stars and Galaxies, ed. C. Payne-Gaposchkin, Harvard Univ Press, New York, p. 19
Baldwin, J.E., Lynden-Bell, D., Sancisi, R., 1980, MNRAS 193, 313
Benedict, G.F., Higdon, J.L., Tolsteyrup, E.V., Hahn, J.M., Harvey, P.M., 1992, AJ 103, 757
Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P., 1989a, ApJ 338, 78
Bertin, G., Lin, C.C., Lowe, S.A., Thurstans, R.P., 1989b, ApJ 338, 104
Bertin, G., 1991, in IAU 146, Dynamics of Galaxies and Their Molecular Cloud Distributions, Kluwer, p. 93
Fig. 5. Fourier spectra for dust penetrated β Population II disks. Note that although the dominant mode is $m=2$, there is an ubiquity of $m=1$ modes as well, but with lower amplitude. Higher order modes (also with lower amplitude than $m=2$) are to be found: NGC 2997 shows a distinct $m=3$ component at $K'$, while NGC 309 and NGC 1637 reveal significant $m=4$ modes in the near-infrared.
Group $\beta$

Fig. 6. Fourier spectra for additional group $\beta$ class members. The dominant mode is $m=2$, with a manifestation of other modes of lower amplitude. Note, for example, that apart from $m=2$, NGC 5247 manifests $m=1$, $m=3$ and $m=4$ modes as well.
Fig. 7. Spectra for dust penetrated group $\gamma$ galaxies with open stellar arms at $K'$. The dominant Fourier mode is $m=2$. Modes of higher order exist (eg. $m=4$ for NGC 5085).
Fig. 8. Contours of the inverse Fourier transform are overlaid on deprojected 2.1µm images of NGC 3223 (Hubble type b; top left) and NGC 5861 (Hubble type c; top right) to indicate the tight winding of the stellar arms of the α class. The pitch angle of the K′ arms becomes more open for the β bin: illustrated are NGC 718 (Hubble type a; middle left) and NGC 309 (Hubble type c; middle right). Finally, the γ bin includes NGC 5085 (Hubble type c; lower left) and NGC 7083 (Hubble type b; lower right) with wide open arms in their evolved disks. There is no correlation between the dust penetrated archetypes and optical Hubble type.