Nuclear bars and blue nuclei within barred spiral galaxies

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Summary.

Multicolour near IR photometry for a sample of 32 large barred spiral galaxies is presented. By applying ellipse fitting techniques, we identify significant isophote twists with respect to the primary bar axis in the nuclear regions of \( \sim 70\% \) of the sample. These twists are identified in galaxies as late as SBbc and are clearly distinguishable from spiral arm morphology. At most seven of the galaxies with isophote twists are inferred to possess secondary (nuclear) bars, the axis ratios of which appear to correlate with morphological type. The remainder may result from triaxial bulges, or from oblate bulges misaligned with the primary bar.

The near IR colour distributions in these data show evidence for (red) circumnuclear star forming rings in 4 galaxies. The majority of the sample (19) also possess striking blue nuclear regions, bluer than typical old stellar populations by \( \sim 0.3 \) mag. in (J–H) and \( \sim 0.23 \) mag. in (H–K). Such blue colours do not appear to correlate with the presence of nuclear rings or pseudo–rings, nor with the activity of the host galaxy (as determined from emission–line spectroscopic characteristics). Several mechanisms to explain this blue colour are considered.

Keywords: galaxies: active – galaxies: nuclei – galaxies: photometry – infrared: galaxies
1 Introduction

The presence of a bar is likely to be an important factor in the fuelling of nuclear (starburst/AGN) activity in many galaxies (e.g. Heckman 1980, Hawarden et al. 1986, Arsenault 1989). An increasing proportion of barred galaxies show evidence of starbursts in the form of active star formation within circumnuclear rings – CNR’s. Good examples of this phenomenon are NGC1097, 4321 and 5728 (Shaw et al. 1993 – henceforth Paper I). This is readily understood as a direct result of gas motions within the barred potential: the bar provides an efficient mechanism to transport gas from the spiral arms to the inner Lindblad resonance (ILR) – or the outer ILR if two exist – where the resulting reservoir of gas provides a source for star formation activity.

Recent theoretical studies (e.g. Shlosman et al. 1989, Pfenniger & Norman 1990) have also highlighted a mechanism whereby an independent, rapidly rotating nuclear bar can provide an efficient means of transporting material from the CNR onto the nucleus, thereby possibly fuelling LINER/Seyfert activity. Some support for this hypothesis may exist in those barred Seyfert galaxies which also possess CNR’s (e.g. NGC1097: Hummel et al. 1987b; NGC3783: Winge et al. 1992; NGC5728: Schommer et al. 1988, Wilson et al. 1993; NGC6951: Boer & Schultz 1993). Shaw et al. (Paper I) stress the significant rôle any such mass transfer of gas may have on the stellar dynamics in the nuclei of barred galaxies.

Inevitably, any study of the fuelling of nuclear activity by a bar requires detailed knowledge of the mass distribution in the central region. In general such information is unavailable as existing observational constraints on the stellar dynamics in the nuclear regions of barred potentials are lacking. The influence of obscuration by dust in the nuclei of barred galaxies (e.g. Baumgart & Peterson 1986) is also a problem, as this places a fundamental limit on photometric studies of the inner regions. The problem is particularly acute given the large number of barred galaxies anticipated to possess nuclear isophote twists suggestive of nuclear bars or coupled star/gas components (Paper I). An important benefit of using near IR photometry is that the effects of dust obscuration are greatly reduced, leading to a more reliable determination of the morphology of the underlying old stellar populations, and ultimately the gravitational potential, in the nuclear regions. No near IR survey of the nuclear regions of barred spiral galaxies has been undertaken. It is thus unclear what proportion of barred galaxies possess nuclear bars, and whether there
is indeed the strong correlation between such bars and the presence of CNR’s implied in Paper I. The degree to which nuclear bars can be distinguished from possible triaxial bulges (e.g. Kormendy 1979, 1982) is also unknown.

In this paper, we present the results of a near IR photometric study of 32 nearby barred spirals which seeks to address such issues. For the reasons given above, we are able to extend studies of the nuclear properties of barred galaxies to significantly later morphological types than has been possible to date. The specific objectives in our study are to determine the proportion of barred galaxies which possess nuclear bars, CNR’s and/or isophote twists in a statistically significant sample. In searching for CNR’s, we make use of the sensitivity of the K–band (2.2 \( \mu m \)) to emission from M giants/supergiants residing in regions of ongoing star formation activity. Analyses of near IR colour distributions are, therefore, an important aspect of this study. Given the limitations inherent in the use of rotation curves to define the pattern speed of a bar, the identification and properties of CNR’s take on added importance if, as is suggested by N–body simulations (e.g. Combes & Gerin 1985), they identify the location of one of the principal resonances in a barred potential.

2 The sample, data acquisition and reduction

2.1 Sample selection

The data in this paper comprise near IR images of 32 large spiral galaxies classified as SAB or SB by de Vaucouleurs et al. (1976). Table 1 collates general properties of these objects.

The present dataset constitutes a subset of our complete sample of large (\( D_{25} \gtrsim 2 \) arcmin), bright (\( m_B \lesssim 12 \) mag.), non–interacting nor irregular barred galaxies. This sample was constructed primarily from Hummel et al. (1987b), Arsenault (1989 – both control and AGN/STB samples), Kormendy (1979), Pogge (1989), Buta & Crocker (1993) and Friedli (private communication). It therefore includes all nearby barred galaxies which possess nuclear rings, pseudo–rings, lenses, that show excessive nuclear H\( \alpha \) fluxes or evidence for nuclear activity (starburst, LINER or Seyfert). The size criterion is chosen so as to improve spatial resolution in the nuclear regions.

The sample presented in this paper is not complete, as it constitutes the first observations acquired from our sample. More general discussions, e.g. relating to the statistical
properties of the sample, will be presented in future papers as and when the observational
data become available. Future data will improve the available spatial resolution by utilising alternative pixel scales. However, the number of objects studied in the present paper is sufficient to constitute a statistically significant subset and thus allows an exploratory investigation of the frequency of nuclear bars, isophote twists and investigating the possible links with CNR’s. The subsample does contain an inherent bias insofar as there was a preferential selection of the larger (though not necessarily more face–on) barred galaxies. However, we stress that an important aspect of this subsample is the broad range of morphological types represented.

2.2 Data acquisition and reduction

Simultaneous J, H, and K (1.2 – 2.2 µm) photometry of the present sample was undertaken using the (256x256 element PtSi array) multichannel IR camera (Ellis et al. 1992) on the KPNO 1.3m between 5 and 14 March 1992. The pixel scale in this configuration is 1.35 arcsec, or 0.10–0.45 kpc/pixel over the distance range of our sample. Integration times of 3x180 sec on each object were interspersed by equal length sky frames, typically offset from the galaxy by ∼10 arcmin. Each object frame was also offset from the other by ∼10 arcsec to minimise contamination by defective pixels. Dark current subtraction was facilitated using equal length dark frames through the run.

Any contaminating objects were removed from the sky offset images, and the resulting frames median filtered to create high S/N “flat–field” frames for each galaxy in each colour. Such images were normalised to a mean of unity and were divided into the corresponding object frame for that particular filter to remove pixel–to–pixel response variations. Such flat–fielded frames were then spatially aligned and summed. Residual edge–effects were removed by subsetting the images and any remaining defective pixels removed by interpolation.

The object frames were then calibrated using observations of 10 faint (J = 6.6–8.4 mag) near IR standards derived from Elias et al. (1982). Typically, between 4 and 8 stars were observed each night. Four of the five nights proved to be highly photometric – the derived zeropoints being consistent throughout the night to within ±0.01–0.02 mag, arcsec$^{-2}$ in all passbands. Data from the single non–photometric night, which affects observations of NGC4754 alone, were calibrated using observations of the standard star HD129653 observed immediately prior to the object frames. Differential airmass correc-
tions were applied to the derived zeropoints using mean extinction coefficients appropriate for the site. The sky background estimates used in each case were median values derived from the object frames directly (in the majority of cases where sky dominates the frames), or from the median filtered sky offset frames (where the objects fill the frame). In the latter, as no significant sky background variations were noted between each sky frame acquired, the mean flux from each of the three frames provides a good estimate of the sky for the objects concerned. Since the J, H and K images were acquired simultaneously, no correction for relative atmospheric extinction differences was necessary when deriving the colour distributions of each object.

The seeing, measured directly from the object frames throughout the run, was 2.0 \((\pm 0.3)\) arcsec FWHM at J, 1.9 \((\pm 0.1)\) arcsec at H and 1.9 \((\pm 0.2)\) arcsec at K. In consequence, ellipse–fitting results derived from the innermost \(\sim 2\) arcsec must be considered highly unreliable.

3 Results

3.1 Primary bar position angles

An important first step in searching for evidence of isophote twists in the nuclei of barred galaxies is an assessment of the orientation of the primary bar.

In each object, visual estimates derived from contour plots and greyscale images of each J, H, K image were compared to those derived from the ellipse fitting procedures discussed below. This is necessary because the latter technique can be unduely influenced by spiral arm morphology (section 3.2). The respective measurements are listed in Table 2, together with their corresponding uncertainties. [Absolute N and E were defined from the known N–S and E–W positional offsets of the standard star observations.] The quoted errors reflect the uncertainty in a particular position angle estimate, and the spread in position angles derived from each passband. Also listed in this table are angles measured from blue and/or red sky survey plates in those objects for which the principal bars can be clearly defined.

Of the 32 objects listed, 3 are too edge–on to allow determination of the primary bar position angle. Such objects will not be discussed further in the context of identifying possible isophote twists. Measures for the primary bar position angles for the remainder are clearly equivalent between the present data and sky survey plate estimates in all cases.
other than NGC3953 and NGC4536. Both galaxies are highly inclined systems (i > 60°, 90° corresponding to edge-on), compromising the evaluation of the position angle from the sky survey plates. In these cases, the measures derived from the present data have been adopted.

3.2 Ellipse fitting

Initial inspection of the data revealed clear evidence for isophote twists (with respect to the primary bar position angles) in 16 objects. With a view to quantifying this, and measuring the degree of isophote misalignment more explicitly, ellipse fitting techniques (e.g. Jedrzejewski 1987) were applied to each (J, H, K) image independently. As a consequence, 21 objects (72% of the non edge-on sample) were found to possess measureable isophote twists, the magnitudes of which are collated in Table 2. [This frequency does not include NGC4321 which possesses elongated inner isophotes and will be discussed further below.]

Such a high incidence of isophote misalignment confirms the expectations in Paper I: this is a common property of the central near IR light distributions of barred galaxies of all morphological types. Figure 1 illustrates this with the 4 most striking examples of isophote twists (NGC3941, 3953, 4613 & 4754), whilst the results of the ellipse fitting to these particular objects are shown in Figure 2.

On the assumption that spiral arms are trailing, we have made an assessment of whether the measured isophote twists trail or lead the principal bar in a similar fashion to that undertaken by Buta & Crocker (1993). Our assessment is illustrated by the sign of the twists in Table 2. The magnitude of the twists, and spatial regions over which they occur, are broadly consistent between each passband (the differences being reflected in the associated errors in this table). Only in the outer regions of some objects are discordant ellipse fitting results derived. In part, these are due to intrinsic colour variations within the disc components (manifest in the case of NGC4321 – Figure 4), but are also a reflection of the impact of the declining quantum efficiency variations of the IR array with wavelength (falling from 6.6% at J to 3.4% at K). The limited spatial coverage of the disc component may be an additional factor for the larger galaxies.

Undoubtedly, NGC4321 and NGC4274 present the clearest evidence of a nuclear bar within the present sample as Figures 3 and 4 clearly show. The nuclear bar in NGC4321 extends to a radius ∼9 arcsec (1.3 kpc) – witness the trough in ellipticity, and peak in \( \cos 4\theta \), profiles at this point (Figure 4). This bar possesses an axis ratio similar to that of
the main galaxy at large radius and is aligned with the inferred primary bar major axis to within 7° (adopting a position angle from Arsenault et al. 1988 and references therein). It is also immediately interior to the CNR evident in our data (Section 3.3) and in emission-line images (Arsenault et al. 1988). Thus, in some respects the properties of the central ∼1.5 kpc of NGC4321 bear a striking similarity to equivalent regions in NGC1097 and NGC5728 (Paper I). Unlike those objects, however, the inner bars in NGC4321 and NGC4274 are closely aligned with the primary bar.

A correlation exists between the scale of the measured isophote twists ($\delta R_{max}$) and bar length – larger bars displaying isophote twists over larger radii (the derived product–moment correlation coefficient of 0.68 is significant at > 99% significance level). An equally significant correlation between $\delta R_{max}$ and morphological type results from the fact that bars in the later type galaxies in this sample tend to be larger. [Note that the anti–correlation between bar and bulge dimensions found by Athanassoula & Martinet (1980) was restricted to objects earlier than Sa.]

Interestingly, the nuclear bar axis ratios in NGC1097, NGC4274, NGC4321 and NGC5728 are markedly smaller than those identified in early type galaxies (e.g. Jarvis et al. 1988), suggesting a possible dependence on morphological type or, equivalently, the nature of the primary bar.

### 3.3 Colour distributions

A striking feature of the derived colour maps is that 19 of the 32 galaxies show particularly blue nuclei, i.e. regions of the colour maps which are considerably bluer than those areas of each galaxy dominated by the bulge component. We refer to these objects as comprising the “blue nuclei” sample. Examples of these structures are given in Figure 5 (b–e). We quantify the magnitude of these colours in Table 3. [The errors quoted throughout this section correspond to standard errors on the mean values for a particular dataset.]

As is evident in this table, a continuum of colours exist between these “blue nuclei” sample and the remainder (henceforth referred to as the “control” sample). The distinguishing property of the former sample is the identification of substructure within the colour maps. Typical nuclear colours within a 0.38 ($\pm$0.02) kpc radius aperture are 0.45 ($\pm$0.06) mag. in (J–H) and 0.02 ($\pm$0.04) mag. in (H–K) for the “blue nuclei” sample. The colours of the “control” galaxies within equivalent apertures are 0.59 ($\pm$0.06) mag. and 0.19 ($\pm$0.04) mag. respectively. Interestingly, even the “control” sample colours are
somewhat bluer than those of typical spiral galaxies: the median colours (i.e. averaged over all morphological types) from Griersmith et al. (1982) are 0.71–0.76 mag. in (J–H) and 0.25–0.30 mag. in (H–K). Similarly, within 6 arcsec diameter apertures, data from Forbes et al. (1992) yield typical colours of (J–H) = 0.83 (±0.14) mag. and (H–K) = 0.44 (±0.16) mag. for a sample of 15 galaxies, only two of which are barred. An IR colour–colour diagram for the galaxies listed in Table 3 is shown in Figure 6, where each galaxy has been identified according to its spectroscopic (nuclear activity) characteristics as presented in Table 1.

The colour maps (e.g. Figure 5) also identify the presence of the CNR’s in NGC4303, 4314 and 4321. These rings are generally redder than all other regions in the galaxy, having colours consistent with those of typical old stellar populations in ellipticals and spiral bulges (Table 4). However, given the spatial distribution of the near IR emission in the rings, a significant contribution from M giants/supergiants in regions of active star formation is likely. This is consistent with the situation in NGC1097 and 5728, where an excellent spatial correspondence is seen between the 2.2µm luminosity peaks and Hα emission within each CNR (Paper I). The inferred radii of the rings identified in the present data (Table 4) are in good agreement with those measures tabulated by Pogge (1989) and Arsenault et al. (1988). The ring colours we derive for NGC4314 agree with those measured by Benedict et al. (1992).

Despite its inclusion in a list of galaxies possessing Hα nuclear rings (Pogge 1989), NGC3351 only shows evidence for a CNR within our (J–K) colour map – Figure 5 (a). The brightest emission regions within this ring have (H–K) ∼0.37 mag. and (J–K) ∼0.99 mag., the latter value being equivalent to that of the nucleus itself. Moreover, the major axis of this ring is aligned with the twisted isophotes identified in Table 2. Both the ring orientation and the location of the maxima in (J–K) coincide exactly with the structure seen in CO and discussed by Kenney et al. (1992).

We have investigated a possible link between CNR’s and nuclear colours by comparing the objects in Table 3 with the catalogue of nuclear rings and pseudo–rings in Buta & Crocker (1993). Although, three of the galaxies in our “blue nuclei” sample also have nuclear rings/pseudo–rings, two of the galaxies in the control sample also show evidence of such rings, implying little evidence of a correlation. Of course, such statistics are only suggestive given the (distance dependent) selection effects inherent in our data and those of Buta & Crocker. Indeed, one must also consider the possibility that the nuclear colours
in the majority of galaxies in Table 3 are contaminated by CNR’s which remain unresolved in our data. This is particularly important given that ILR’s – supposedly identifying the presence of CNR’s (Combes & Gerin 1985) – show a wide variation in size within the N–body simulations conducted to date (e.g. a factor of two in Paper I). There also exists the possibility of temporal variations in the size of CNR’s (Combes et al. 1992).

Rings in our data would remain unresolved if their radii were \( \sim 3 \) pixels or less, corresponding to \( \sim 0.5 \) kpc since the distance to those blue nuclei galaxies in Table 3 not identified as possessing CNR’s is typically 28.0 (\( \pm 1.5 \)) Mpc. The possibility therefore remains that the majority of colours in Table 3 are influenced by the presence of unresolved CNR’s. Clearly, since the CNR’s unambiguously identified in the present dataset are very red (Table 4), their presence in the remaining data would imply that even bluer underlying colours exist within these nuclear regions. Possible sources of such blue colours are discussed in Section 4.2 below.

4 Discussion

4.1 Nuclear bars and triaxial bulges

A primary aim of the present study was to quantify the occurrence of isophote twists in the nuclear regions of barred galaxies. As Table 2 graphically illustrates, such twists are common in the near IR. Fully \( \sim 70 \% \) of the non edge–on galaxies in the present sample display measurable twists in galaxies ranging from SB0 to SBbc. It is therefore important to identify the mechanism(s) by which such twists arise. Since contamination by spiral arms is minimal in the regions concerned, nuclear bars or misaligned/triaxial bulges present the most obvious cause.

The nature and properties of nuclear bars have been investigated in several theoretical studies (e.g. Shlosman et al. 1989, Pfenniger & Norman 1990). Only two investigations have used constraints imposed by observations of real galaxies. In Paper I, Shaw et al. argued that twists result from the dynamical influence of the gas component (on the stars) as the gas follows the stable \( x^2 \) orbits immediately interior to the ILR. Conversely, Friedli & Martinet (1993) view these systems as nested double barred galaxies. A principal difference between the simulations conducted in these studies is the role of dissipation. In Paper I viscosity is the mechanism by which the gas leads the stars – giving rise to the observed twists. Dissipation is less important in the picture described by Friedli &
Martinet (1993). In their scheme, the twists are a direct manifestation of two misaligned bars possessing grossly different pattern speeds.

We have identified what proportion of those galaxies displaying isophote twists (other than NGC4321) are candidates for possessing nuclear/misaligned bars. In doing so, three methods are available to us. In the first instance, we have compared the spatial dimensions of the observed twists ($\delta R$) to the lengths ($L$) of the principal bars (Table 2). In the mean, $\delta R/L$ extends from 0.16 ($\pm 0.02$) to 0.67 ($\pm 0.05$), neglecting NGC4321 – i.e. considerably in excess of the 0.1–0.2 inferred by Friedli & Martinet (1993) or the values of 0.14 and 0.09 observed in NGC1097 and 5728 respectively (Paper I). The only likely nuclear bar candidates on these grounds would be NGC4643 and, possibly, NGC4274. Moreover, in the hypothesis advanced in Paper I, the observed twists must lie immediately interior to the radius of the CNR. Again neglecting NGC4321, the mean dimensions of the observed twists have inner and outer radii of 0.8 ($\pm 0.1$) kpc and 2.9 ($\pm 0.3$) kpc respectively, seemingly larger than the typical radii of CNR’s (Paper I and references therein).

A second discriminant comes from the misalignment angles in Table 2. In agreement with the (limited) sample presented by Buta & Crocker (1993), the isophote twists lead or trail the spiral arms in roughly equal proportions, even for the most face–on galaxies in the sample. [The measures in Table 2 have not been deprojected as the measured inclination angles are derived from projected axis ratios and are notoriously unreliable – depending, for example, on spiral arm morphology.] This suggests that relatively few of the objects in Table 2 are candidates for double barred galaxies, although a more reliable conclusion would require accurate deprojection.

Finally, we consider the orbital families in the barred potential. Stable periodic orbits cannot cross (Sparke & Sellwood 1987, Athanassoula 1992). Therefore, the minor axis dimension of the primary bar (identifying the x1 orbital family) corresponds to the maximum dimension of any nuclear bar and thus the radius of any CNR. We have determined the axis ratios of the principal bars from the J–band images of each galaxy with measurable isophote twists in Table 2. No deprojection was undertaken – we assume the nuclear and primary bars are coplanar and that projection foreshortens the dimensions of each equally. Comparison of the minor axis dimensions to the radial scales of the twists listed in this table suggests that nuclear bars are present in NGC4262, 4274, 4314 and 4643, with NGC4371 and 4754 being additional, though less well–defined, candidates.
In conclusion, at most 7 of the 22 objects displaying near IR isophote twists are likely to possess nuclear/misaligned bars of the type envisaged in Paper I or Friedli & Martinet (1993). Using the present data, a discrimination between these two studies would require a detailed investigation of the role of projection. As one must take into account the intrinsic figure of the bar itself (Paper I), this analysis is beyond the scope of the present paper. Observationally, a more definitive conclusion would result from detailed 2D stellar and gas dynamics of galaxies possessing twisted isophotes.

It is possible that the observed twists in the remaining galaxies result from the presence of triaxial bulges (e.g. Kormendy 1979, 1982). However, the complex transition between bulge and primary bar luminosity components renders unreliable any results derived from photometry alone. In fact, the observed twists could readily result from a misalignment between a conventional (oblate) bulge and the principal bar. The stability of such a configuration remains to be determined, although the frequency of twists in the present sample implies such a configuration must be stable. A definitive identification of triaxiality in these galaxies could only be undertaken by combining full 2D luminosity decomposition with extensive stellar and gas kinematics.

4.2 The significance of blue nuclear colours

Many galaxies in the present sample display blue nuclear colours. Indeed, even in those galaxies displaying CNR’s, blue nuclei are evident on scales considerably smaller than the inferred dimensions of rings (Figure 5). We consider two mechanisms by which this blue colour could arise.

4.2.1 Extinction variations

The first results from a reduction in extinction within the nuclear regions. The reddening vector in Figure 6 suggests a change of $A_v \sim 1$ mag. would be sufficient to bring the IR colours of the majority of the sample into agreement with those of typical old stellar populations. Reduced extinction may result from the highly collimated nature of the gas distribution in a bar. The gas is principally restricted to the leading edges of the bar (as in, for example, NGC613: Hummel et al. 1987a, and NGC1097: Gerin et al. 1988). The region interior to the corotation radius, but outside the bar itself, is thus largely devoid of gas in many barred galaxies. An aperture $\sim 0.4$ kpc in radius (Section 3.3) would encompass such regions, possibly leading to a reduction in the near IR colour indices.
when compared to non–barred galaxies. Optical colours would not support this assertion, since the nuclear colours derived are invariably very red. However, large scale surveys of near IR galaxian colour distributions remain to be undertaken.

4.2.2 Nuclear activity

The blue colour could be an observational consequence of nuclear activity if it implies the existence of starbursts with suitable star formation properties. This hypothesis is favoured by the fact that, of the 13 galaxies in the sample whose nuclei have the spectral characteristics of starbursts/LINERS (Arsenault 1989 and references therein), 10 have unusually blue nuclei. Conversely, only 9 galaxies not showing such activity also possess blue colours. Formally, sampling theory suggests that these ratios differ at the 93.6% significance level using the “two–tailed” test. In reality, however, the results are only suggestive given the limited samples involved and the large apertures used in the spectral classification (4–8 arcsec diameter – Keel (1983) – such that much of the emission from the starburst candidates may come from CNR’s rather than the nuclei directly).

A link between blue colours and nuclear activity could be understood as resulting from the featureless blue continuum (FBC) detected in many Seyferts and LINERS (e.g. Yee 1983). This FBC is bluer (at optical wavelengths) than the colours of spiral galaxy bulges, and may correspond to the continuum in a young starburst (Terlevich & Melnick 1985). A difficulty with this hypothesis results from the fact that the blue colours in Table 3 are often distributed in a collimated structure (Figure 5), and thus are more extended than the (unresolved) FBC in most active galaxies. Moreover, the contribution of the FBC is likely to be small in the near IR. The blue colours in our sample are observed even in galaxies which are not classified as active whilst, in the scheme of Terlevich & Melnick (1985), “blue LINERS” are galaxies which have already evolved beyond a Seyfert 2 phase of activity.

There also exists the intriguing possibility of a relationship between the blue nuclear structures (Figure 5) and the anisotropic radiation field in active galaxies. Specifically, these elongated blue structures may correspond to the blue, collimated and extended emission–line regions (EELR’s) commonly observed in Seyferts (e.g. Haniff et al. 1988, Wilson et al. 1988). The suggestion of a strong causal relationship between nuclear activity and gas motions within the innermost regions of a barred potential (Paper I and references therein) would imply a correspondence between the orientations of the EELR
and any nuclear bar.

To investigate this possibility further, we have measured the alignments of the (7) extended blue regions in our colour maps. They are compared to the orientations of the nuclear isophotes in Table 5. There appears to be a particularly close correspondence between these respective P.A.’s in NGC3412, 3945, 4536 and 4643. Even in the remaining cases, it is clear that there exists a considerable misalignment between the extended blue nuclear regions and the orientation of the primary bars. More extensive observational data are required to further investigate this possible correspondence.

Near IR data for a small sample of active galaxies are presented by Hunt & Giovanardi (1992). More detailed studies of the 2D near IR luminosity distributions in LINERS/starbursts (Forbes et al. 1992) suggest the nuclei of such galaxies to be redder than typical old stellar populations – particularly in (H–K). The colours of the LINERS/starbursts in Forbes et al. are also consistent with those of Seyfert I nuclei (Kotilainen et al. 1992b, Kotilainen & Ward 1994), although the emission mechanisms are likely to be quite different. These red colours have most recently been interpreted as implying re-radiation from hot dust at 2.2µm, influenced by the proximity to the active nucleus (Kotilainen & Ward 1994). The contribution from M giants/supergiants is, however, likely to be an important factor in starbursts.

Unfortunately, there appear considerable uncertainties regarding the colours derived for these LINER/starburst and Seyfert I samples. Estimates of the sky background are unreliable in data of such limited spatial coverage. Furthermore, the removal of a nuclear (non-stellar) contribution to each passband is highly uncertain given the assumptions of azimuthal symmetry imposed, difficulties in the assignment of a suitable PSF and the unreliable nature of complex luminosity profile deconvolution given the limited data available (Kotilainen et al. 1992a). The apertures used by Kotilainen & Ward (1994) are not sufficiently small to eliminate significant contributions from circumnuclear star formation in some objects. Interestingly, of the 4 Seyfert galaxies in our sample (Table 1), only NGC4593 has an unusually red (H–K) colour. Our values of (J–H)=0.67 mag. and (H–K)=0.44 mag. for this object are in reasonable agreement with those of Kotilainen & Ward (1994) over similar apertures.

Clearly, detailed studies of the near IR luminosity distributions of LINER/starburst and Seyfert galaxies must await observations with high spatial resolution and large areal coverage.
5 Conclusions

In this paper, we present near IR photometry of 32 large, non-interacting barred galaxies. Fully 21 of the 29 non edge-on objects in this sample display measurable inner isophote twists with respect to the primary bars, thereby confirming the frequency of this phenomenon inferred by Shaw et al. (1993). Such twists are identified in galaxies as late as SBbc.

Comparisons have been undertaken between the scale of such isophote twists and the typical dimensions of nuclear bars, circumnuclear rings (CNR’s) and the inferred maximum dimensions of the x2 orbital family within each primary bar. We conclude that 7 of these galaxies may possess a secondary (nuclear) bar misaligned from the primary. NGC4274, 4321 and 4643 present the clearest evidence of this morphology. There appears to be a correlation between the axis ratios of the inner and primary bars, as the nuclear bars are much thinner and more distinct in later type galaxies. However, we find no evidence of a correlation between twisted near IR isophotes and the presence of CNR’s. Twists in the remaining galaxies may reflect the presence of triaxial bulges or of oblate bulges misaligned with the principal bar.

The near IR colour distributions in our sample yield evidence for very blue structures within the nuclei of 19 galaxies – these regions being bluer than typical old stellar populations by $\sim0.30$ mag. in (J–H) and $\sim0.23$ mag. in (H–K). These blue colours do not appear to correlate with the presence of CNR’s.

It is unlikely that these blue colours result from a contribution from young giants/supergiants within unresolved circumnuclear star forming rings as the CNR’s observed in the present data are all red and probably dominated by emission from M stars. If such blue regions reflect reddening variations within the nuclei for objects with typical elliptical/bulge colours, a reduction in extinction of $A_v \sim1.0$ mag. is implied. This may result from the geometry of the gas distribution within the corotation radius of the barred potential.

Interestingly, 3 of the 4 galaxies showing clear evidence for resolved CNR’s in our data also possess blue nuclei – one of these being a Seyfert, one a LINER and one a starburst. This may be suggestive of a link with nuclear activity, although the extended nature of the blue nuclear colours, even in galaxies not classified as active, argues against their resulting from the featureless blue continuum observed in many Seyferts/LINERs.
However, a general equivalence between the orientations of these blue regions and the innermost nuclear isophotes may suggest that the former are a manifestation of the extended, blue, emission-line regions commonly identified in some Seyfert galaxies.

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**Figure captions**

**Fig. 1:** Contour plots from subregions of the J-band images of NGC3941, 3953, 4643 and 4754. In all cases, N is down, E to the left. The axes are marked in pixels (1 pixel = 1.4 arcsec) and the data are contoured from 14.0 to 18.4 mag. arcsec$^{-2}$ in 0.4 mag. arcsec$^{-2}$ intervals. The primary bar position angles, derived as discussed in the text, are shown by the dashed lines.

**Fig. 2:** Plots of the radial variation of position angle, ellipticity, cos $4\theta$ and azimuthally averaged surface brightness ($\mu$) derived from ellipse fitting to the galaxies displayed in Figure 1. The profiles for each passband are distinguished by the symbols shown in the legend accompanying the lower right hand panel for each galaxy. The horizontal dashed lines in the position angle profiles denote the P.A. of the primary bars, whilst the arrow identifies the inferred minor axis dimensions of these bars.

**Fig. 3:** As Figure 1, but for NGC4274 (a) and NGC4321 (b). An expanded plot of the central region of (b) is given in (c). Data in (a) are contoured using the levels adopted in Figure 1. In (b) contours are plotted from 14.0 to 17.6 (J) mag. arcsec$^{-2}$ in 0.4 mag. arcsec$^{-2}$ intervals, whilst in (c) contours are from 14.0 to 16.2 mag. arcsec$^{-2}$ in 0.2 mag. arcsec$^{-2}$ intervals.

**Fig. 4:** As Figure 2, but for NGC4321.

**Fig. 5:** Greyscale plots of the 2D colour distributions within: (a) NGC3351 (J–K); (b) NGC3945 (H–K); (c) NGC4303 (J–H); (d) NGC4321 (J–H) and (e) NGC4754 (J–H). Display levels are: (a) 0.5 (black) to 1.0 (white) mag.; (b) 0.0 to 0.35 mag.; (c) 0.35 to 0.7 mag.; (d) 0.25 to 1.2 mag. and (e) 0.3 to 0.65 mag. The spatial coverage is: (a) 91x92 arcsec; (b) 117x109 arcsec; (c) 127x139 arcsec; (d) 206x186 arcsec and (e) 104x135 arcsec.

**Fig. 6:** Near IR colour-colour diagram of the present sample. Also displayed is the region occupied by typical old stellar populations (circle), and the track delineated by a ~30% contribution from a 600 K black body. The influence of a 10% contribution from hot (T=200K) dust at 2.2$\mu$m and a reddening vector of $A_v = 1$ mag. are also shown. The galaxies in the present sample are plotted according to their classifications inferred from their emission–line spectra in Keel (1983). Typical uncertainties on both colours are plotted in the lower right corner. Galaxies identified as Seyferts in Veron–Cetty & Veron (1989) are marked by filled symbols.

**Table captions**

**Table 1:** Properties of the present barred galaxy sample.

**Table 2:** Summary of results derived from ellipse fitting to the sample galaxies.

**Table 3:** Results derived from analyses of the colour distributions in the sample galaxies.
Table 4: Colour indices for the nuclear rings in NGC3351, 4303, 4314 and 4321. Ring dimensions are quoted as major x minor axes, derived from the (J–H) colour maps or, in the case of NGC3351, (J–K).

Table 5: Comparison of the orientations of the extended blue regions in the colour maps and the nuclear isophote orientations listed in Table 2.
Notes to Table 1

**source of type**: RC2 – de Vaucouleurs, de Vaucouleurs & Corwin (1976); dVB – de Vaucouleurs & Buta (1980).

**dist.**: Object distance, taken from recessional velocities in Palumbo, Tanzella–Nitti & Vettolani (1980), using the distance moduli in Bottinelli et al. (1984), or – for NGC4314 – the distance estimated by Garcia–Barreto et al. (1991). An H₀ of 50 km s⁻¹ Mpc⁻¹ is assumed throughout.

**classification**: Object classification from inclusion within the starburst/A.G.N. or control samples of Arsenault (1989).

**comments**: nuc. ring – nuclear ring; opt. twists – twists in optical isophotes with radius.

**source of comments**: BC93 – Buta & Crocker (1993); VV89 – Veron–Citty & Veron (1989); D92 – Devereux, Kenney & Young (1992); K79 – Kormendy (1979); J88 – Jarvis et al. (1988); A88 – Arsenault et al. (1988).
Notes to Table 2

col. 2 : A = anticlockwise, C = clockwise, measured from the POSS or the present dataset assuming spiral arms are trailing.

cols. 3–6 : POSS corresponds to position angles defined from the POSS survey plates, whilst “ellipse fit” lists those derived from ellipse fitting to the present dataset (averages of all 3 near IR frames with the exception of NGC3945 which is measured from the J–band image alone).

col. 7 : Galaxy inclination angles derived from log $R_{25}$ measures in de Vaucouleurs, de Vaucouleurs & Corwin (1976) assuming an intrinsic disc axial ratio of 0.2.

cols. 8, 9 : Offset between inner near–IR isophotes and those of the principal bar component. Measures derived from ellipse fitting results except for NGC3945, NGC4340 and NGC4371 where $\theta$ is measured directly from the images. For NGC3351, values refer to the J and H images only. Sign of $\theta$ identifies whether the inner misaligned isophotes lead (+) or trail (–) the primary bar. In galaxies for which the sense of rotation is undefined, the isophote twists are denoted by “±”.

cols. 10, 11 : Spatial scale over which the isophote twists are observed.

col. 12 : Radius of the primary bar, measured from the J–band images except for NGC4321 which comes from the estimate of Arsenault et al. (1988).

col. 13 : The spatial scale of the misaligned isophotes ($\delta R$) expressed as a fraction of the radius (L) of the primary bar.
Notes to Table 3

col. 2 : Aperture radius (kpc) over which mean colour indices in cols. 3,4 correspond. For the “control” sample, an aperture of 2 pixels was adopted throughout.

cols. 3, 4 : Colour indices with errors corresponding to standard deviations about these mean values within the specified apertures.

cols. 5, 6 : Magnitudes of colour differences between nuclear structures in colour maps and the colours of the surrounding regions.

col. 7 : Comments on structures evident in colour maps.
Notes to Table 5

col. 2: Colour map used in evaluation of entries in cols. 3 and 4. All corresponds to J–H, H–K and J–K colour maps.

col. 3: Position angle of the elongated blue structures evident in the colour maps cited in col. 2. Where several colour maps have been used, values quoted are weighted means.

col. 4: Differences between PA_{col} in col. 3 and the position angle of the primary bar (as defined in Table 2). Measured in the sense PA_{col} – PA (primary bar).

col. 5: θ measures in Table 2, expressed in the sense PA (inner isophotes) – PA (primary bar). The sign of θ may differ from that in Table 2 as the latter measures identify whether the inner isophotes trail or lead the primary bars.