On Bars, Bulges and Fuelling of Active Galactic Nuclei

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ABSTRACT

Both fuelling of a central black hole and the build-up of bulges are – at least theoretically – facilitated by non-axisymmetric potentials. It is argued here that the recently established surface brightness division between bulge-dominated galaxies that dominate the local type 2 AGN luminosity function, and disk-dominated galaxies that host (at best) weak AGN can be understood in terms of a simple bar-instability criterion.

Subject headings: galaxies: active – galaxies: bulges – galaxies: evolution – galaxies: spiral

1. Introduction: The Observed Surface Density Criterion

Kauffmann et al. (2003) have recently demonstrated, using the vast dataset on nearby galaxies from the Sloan Digital Sky Survey, a stellar mass, and equivalent stellar surface mass density (or surface brightness), criterion for the separation of bulge-dominated and disk-dominated galaxies (as classified by the value of the concentration parameter). They find that bulges dominate for systems of stellar mass greater than $\sim 3 \times 10^{10} M_\odot$, with a corresponding mean stellar surface density interior to the half-mass radius of $\mu_* \gtrsim 3 \times 10^8 M_\odot$/kpc$^2$. Heckman et al. (2004) analysed the Active Galactic Nuclei (AGN) population within the SDSS dataset, and concluded that the critical surface density also marked the onset of AGN activity, in terms of contributions to the volume-weighted [OIII] luminosity (their Fig. 4). They find that significant AGN activity occurs only for $\mu_* \gtrsim 3 \times 10^8 M_\odot$/kpc$^2$, peaking at $\mu_* \sim 10^9 M_\odot$/kpc$^2$.

The surface density measurement used for the SDSS sample of Kauffmann et al. is the mean surface density within the half-light radius, derived from a combination of model fits to the spectra to determine the total stellar mass, and to the imaging data to determine the
Petrosian half-light radius. The well-known ‘Freeman Law’ (Freeman 1970) for the central surface brightness in the B-band of galactic disks, $I_0 = 21.65 \text{ mag/arcsec}^2$, corresponds to a central stellar surface density of $145 (M/L)_B \text{ M}_\odot/\text{pc}^2$ (Fall 1981). A thin exponential disk of scale length $\alpha^{-1}$ has the surface density profile

$$\mu(R) = \mu_0 e^{-\alpha R} = \frac{\alpha^2 M_D}{2\pi} e^{-\alpha R},$$

(1)

where $\mu_0 = \frac{\alpha^2 M_D}{2\pi}$ is the central surface density. Thus for disk-dominated galaxies, assuming an exponential stellar disk, the half-light radius is $R_e = 1.67\alpha^{-1}$ and the mean surface density within this radius, for fixed $M/L$, is

$$<\mu> = \frac{1}{2} \frac{M_D}{\pi R_e^2} = \frac{\mu_0 \alpha^2}{\alpha^2 \pi (1.67)^2} = \frac{\mu_0}{(1.67)^2} = 0.36\mu_0.$$

(2)

Adopting a typical $(M/L)_B \sim 2$ from the disk models of Bell & de Jong (2001) gives for Freeman’s Law $\mu_0 \simeq 3 \times 10^8 \text{M}_\odot/\text{kpc}^2$, or $<\mu> \sim 10^8 \text{M}_\odot/\text{kpc}^2$. As shown for example by de Jong (1996), ‘Freeman’s Law’ is better understood in terms of an upper limit for the central surface brightnesses of disks, rather than giving the characteristic value. The sample of de Jong (1996) has an upper limit to the B-band central disk surface brightness of $I_0 \lesssim 20 \text{ mag/arcsec}^2$, corresponding to $<\mu> \sim 4.6 \times 10^8 \text{M}_\odot/\text{kpc}^2$. The similarity to the SDSS-derived result is striking.

Such an upper limit to the surface density of galactic disks has variously been attributed in the literature to instabilities. For example, Dalcanton, Spergel & Summers (1997; their Figure 5) use the Toomre-\(Q\) criterion (Toomre 1964) to provide a understanding of ‘Freeman’s Law’. The Toomre-\(Q\) parameter is to be evaluated locally, as a function of radius, and involves both the local disk surface density and disk velocity dispersion. Mo, Mao & White (1998; their Figure 3), considered the mass fraction of the disk and disk angular momentum parameter together, and defined a region of parameter space in which disks are stable by the Efstathiou, Lake & Negroponte (1982; hereafter ELN) criterion and did not consider models that were not stable by their criterion. Zhang & Wyse (2000) similarly interpreted the ELN criterion in terms of overall baryonic mass fraction and angular momentum parameter.

In the present paper we show that the physical conditions necessary for the onset of bar-instability in disks (Efstathiou, Lake & Negroponte 1982) can be written as a pure surface density criterion. We further show that the critical value of the surface density is very close to that found by Kauffmann et al. and Heckman et al. to divide galaxies into bulge-dominated, AGN-bright galaxies and disk-dominated, AGN-faint galaxies. We argue this may be understood if non-axisymmetric perturbations such as bars are critical for efficient fuelling of a central supermassive black hole (SMBH), and for bulge creation. We suggest
that ‘classical’ $R^{1/4}$ bulges may be more associated with AGN activity than ‘exponential’ bulges, possibly indicating the importance of gaseous dissipation for both classical bulge formation and AGN activity.

2. What turns AGN on and off?

The AGN phenomenon depends on three schematic components (Gunn 1979) viz. the central engine, accepted to be a massive $\gtrsim 10^6 M_\odot$ black hole; the fuel for the central engine, either in stellar or gaseous form; and lastly the mechanism by which the fuel is delivered to the engine. Thus any trend in the occurrence or strength of the AGN phenomenon should be caused by a variability in the occurrence of either the engine or the fuel, or in the efficiency of fuelling. Black holes once formed are persistent, so it is more plausible that variations in AGN activity are related more to fuelling variations – either in the amount of fuel or in the efficiency of transportation to the black hole.

Angular momentum provides a barrier to the inflow of fuel and must be lost for fuel be accreted by a central SMBH. The importance of triaxial perturbations in the central potential well to the efficiency of gas transportation inwards was reviewed by Shlosman, Begelman & Frank (1990). These authors envisage that bars of gas and of stars form at a range of radii within a given host galaxy of an AGN (‘bars within bars’; Shlosman, Frank & Begelman 1989), with each bar playing a distinct role in the accretion process onto the black hole; the maximum attainable accretion rate of gas onto a black hole can be increased by an order of magnitude if the potential is triaxial rather than spherical. Similar increases in theoretical fuelling efficiency are achieved for stellar fuel if the potential is non-axisymmetric (Norman & Silk 1983).

Deep imaging with the Hubble Space Telescope, particularly in the infrared, has revealed a wealth of structure, including bars-within-bars, in the central regions of both AGN and non-AGN host galaxies (e.g. Carollo et al. 2002; Erwin & Sparke 2002; Martini et al. 2003). Laine et al. (2002) found a significantly higher rate of bars in Seyfert galaxies than in non-Seyfert galaxies, on both kpc and sub-kpc scales. However, as noted by those authors, even at the H-band the effects of extinction and star formation can confuse the identification and characterization of inner bars, so that imaging surveys are not the ideal approach. As suggested by the anonymous referee of this paper, 2D spectroscopy could provide an alternative approach.

Several studies have investigated mechanisms by which a bar or triaxial perturbation is destroyed by a central compact object, suggesting a self-limiting process of bar fuelling
and growth of a central SMBH (e.g. Hasan & Norman 1990; Shen & Sellwood 2004). Bulges may be formed from the disrupted bars (e.g. Norman, Sellwood & Hasan 1996; Pfenniger 1999); the required mass ratio of central compact object to bar, for destruction of the bar, is of order the mass ratio of quiescent SMBH to bulge in nearby galaxies (but depends on several parameters, such as density e.g. Shen & Sellwood 2004). Even if the central compact object does not destroy the bar, the efficiency of fuelling may be disrupted by the changes in orbital structure induced by scattering of stars by the central object (e.g. Sellwood & Moore 1999; El-Zant et al. 2003).

But how do bars form initially? Many simulations have demonstrated that cold, sufficiently self-gravitating disks, both stellar and gaseous, form bars (e.g. Ostriker & Peebles 1973; Toomre 1977; Efstathiou, Lake & Negroponte 1982; Christodoulou, Shlosman & Tohline 1995; Bottema 2003). Stability may be imposed either by decreasing the level of self-gravity, for example by embedding the disk in a dark halo, or by addition of a dense core (Toomre 1981; Sellwood 1989; Sellwood & Evans 2001). A simple criterion for the instability of a thin exponential stellar disk within a dark halo that provides a flat rotation curve was derived by Efstathiou et al. (1982; hereafter ELN), namely bar-instability occurs if

\[
\frac{v_m}{(\alpha M_D G)^{1/2}} < 1.1, \tag{3}
\]

where \(v_m\) is the maximum rotational velocity, \(\alpha^{-1}\) is the disk exponential scale-length and \(M_D\) is the total disk mass. For a purely gaseous disk the critical value of this ratio is somewhat reduced, to 0.9 (Christodoulou et al. 1995). A finite thickness, reflecting a hotter disk, provides some stability. As may be derived from the simulations of Bottema (2003; his Tables 1 & 2), disks with an exponential scale-height up to \(\sim 300\) pc, consistent with observations, and initial gas fractions of 20%–50%, follow the ELN criterion. Indeed the ELN expression has been shown to be a fairly robust empirical criterion, irrespective of the detailed physics driving the instability, for models of late-type (small-bulge) disk galaxies (e.g. Bottema 2003; O’Neill & Dubinski 2003). These are the systems to which we will apply this criterion in this paper.

The ELN criterion was re-interpreted by Mo, Mao & White (1998) in terms of the ratio of fractional disk-to-halo mass, \(m_d\), to disk spin momentum parameter, \(\lambda_d\) such that instability occurs for

\[ m_d > \lambda_d. \]

However, in the present context it is more illuminating to re-write this criterion in terms of a critical surface density, as follows.
2.1. The disk surface density criterion for bar instability

As noted above, an exponential disk has central surface density

\[ \mu_0 = \frac{a^2 M_0}{2 \pi}. \]

Upon substitution of this expression in the original ELN criterion, equation (3) above, one obtains bar instability for

\[ \mu_0 > \frac{v_m^4}{(1.1)^4 2 \pi M_D G^2}. \]

The Tully-Fisher relationship can then be used to eliminate parameters on the righthandside, assuming that the stellar mass is dominated by the disk. As is well-known, a straightforward \( L \propto M \propto v_m^4 \) relation, together with assumed virial equilibrium, immediately gives a constant surface density (Aaronson, Huchra & Mould, 1979, particularly their Appendix). Most recent investigations of the Tully-Fisher relation however do not find a slope of 4. Verheijen (2001) provides correlations between \( v_m \) and the \( K' \)-band luminosity, a good proxy for total stellar mass. From his Table 4:

\[ M_{K'} = 3.19(\pm 0.92) - 10.5(\pm 0.4) \log(2 v_m), \]

with the units of \( v_m \) here being km/s. In what follows, we will adopt the best-fit values of the slope and zero-point in this relation, but one should keep the quoted uncertainties in mind.

Adopting \( M_{K'}^{\odot} = +3.2 \simeq 3.19 \) for the absolute magnitude of the Sun (see Table 7, Verheijen 2001) and \( (M/L)'_K = 0.5 \), following the K-band models of Bell & de Jong (2001; note that they found only a factor of two total variation in the K-band stellar M/L of disk galaxies across the Hubble sequence), reduces this expression to:

\[ \frac{M_D}{M_\odot} = 9.5 \left( \frac{v_m}{\text{km/s}} \right)^{4.2}, \]

or with velocities in cm/s

\[ M_D = 1.9 \times 10^{13} v_m^{4.2} \text{ g}. \]

Substitution of the resulting expression for \( v_m \) into equation (4) above gives bar instability for

\[ \mu_0 > 5.7 M_D^{-0.04} \text{ g/cm}^2, \]

and equivalently in terms of mean surface brightness within the half-mass radius

\[ < \mu > > 2 M_D^{-0.04} \text{ g/cm}^2. \]

The mass of the disk may be eliminated from this expression by use of the correlation between mean surface density within the half-light radius and stellar mass found by
Kauffmann et al. (2003), again assuming that we are in the regime where the stellar mass is dominated by the disk. This is:

\[
< \mu > \equiv \mu_*(M_\odot/kpc^2) = 3 \times 10^8 \left( \frac{M_D(M_\odot)}{3 \times 10^{10}} \right)^{0.54}.
\]

Adopting this scaling between mean surface density and central surface density provides a mean disk surface density criterion for bar instability of

\[
< \mu > > 1.7 \times 10^8 \quad M_\odot/kpc^2.
\]

We have implicitly assumed purely stellar disks. As noted above, the ELN criterion remains valid for reasonable gas fractions, with the total disk mass being the relevant parameter. Given that the disk galaxies with higher surface density tend to be earlier morphological types, with lower gas fractions (see e.g. de Jong 1996), the uncertainties are within the order of magnitude estimates of this paper.

One might in principle use the ‘baryonic Tully-Fisher’ relationship (e.g. McGaugh et al. 2000; Bell & de Jong 2001) in place of the stellar Tully-Fisher relation; however this would necessitate the further assumption of equal (exponential) scale lengths for the gas and stars to combine with the ELN criterion. In addition, combination with the observed stellar surface density – stellar mass would require knowledge of the gas/star fraction. We have thus not attempted this.

3. Discussion

The critical mean disk surface density above, equation (7), is remarkably close to the surface density found by Kauffmann et al. to characterise bulge-dominated galaxies, and by Heckman et al. to characterize the onset of significant contributions to the volume-averaged Type 2 AGN luminosity function, discussed in section 1. One expects the stellar surface density to increase once a bar forms, since the subsequent gas fuelling to the central regions will inevitably be accompanied by star formation, as seen both in observations and simulations. Thus the fact that the derived criterion for bar instability is a factor of two or so below the observationally derived surface density for bulge dominance and AGN activity is not surprising. Indeed, Heckman et al. find that at higher stellar surface densities the ratio of star-formation rate to black-hole fuelling rate is a constant, \( \sim 10^3 \), and these authors discuss how the correlation between fossil supermassive black hole (SMBH) mass and bulge stellar mass in nearby bulge-dominated galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000) could arise from this star-formation rate – AGN fuelling relation.
In the context of the connections among bars, AGN and bulges, it may be relevant that all AGN in the sample of Carollo et al. (2002) were hosted by a classical \( R^{1/4} \)-bulge, rather than an ‘exponential’ bulge (this trend was not commented on by those authors). Exponential bulges may form from bars through secular stellar dynamical processes (e.g. Pfenniger 1999; Debattista et al. 2004), while \( R^{1/4} \) bulges may require efficient gaseous dissipation and accompanying efficient star formation (e.g. Wyse 1998; 1999). Thus the dissipation that is probably required to fuel SMBH may preferentially also lead to the formation of \( R^{1/4} \) bulges.

The picture that appears most consistent with the data is that bulges and AGN are causally linked with bars, resulting from instability in high-surface density disks. While this is not a new picture (e.g. Sellwood & Moore 1999), the required elements are now better-established. The high-surface density disks could either form directly from initial conditions, such as low values of the spin parameter, \( \lambda_d \) (Dalcanton, Spergel & Summers 1997) perhaps combined with high disk mass (Mo, Mao & White 1998; Zhang & Wyse 2000), or evolve towards instability through mass re-distribution, for example by viscous processes (e.g. Zhang & Wyse 2000). Exponential bulges and \( R^{1/4} \) bulges may require different amounts of gaseous dissipation and star formation rates. The link between AGN and \( R^{1/4} \) bulges seen in the sample of Carollo et al. (2002) should be investigated with a larger sample. Dissipative formation of bulges and associated fuelling of a central black hole is envisaged in the model for quasars of Silk & Rees (1998). Lower luminosity AGN may form similarly.

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