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THE EFFECT OF BARS ON THE FUELING OF STAR FORMATION AND NONSTELLAR ACTIVITY IN GALAXY NUCLEI

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ABSTRACT. Theoretical studies suggest that large-scale stellar bars can be highly effective in delivering gas to the central few hundred parsecs of a spiral galaxy, which may then initiate rapid star formation. Further instabilities may lead to additional inflow to physical scales relevant for active galactic nuclei. We test these predictions in light of recent observations. Compared to unbarred spirals, barred galaxies of type S0-Sbc have a higher probability of exhibiting nuclear star formation, as well as a higher formation rate of massive stars; neither effect is present in spirals of later morphological type. Bars, on the other hand, do not have an obvious influence on active nuclei. We discuss the implications of these findings for the fueling of central star formation and active nuclei.

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1. INTRODUCTION

This contribution presents an observational overview of the influence of bars on star formation and nonstellar activity in the centers of nearby spiral galaxies. The non-axisymmetric gravitational perturbation of a large-scale stellar bar or oval distortion in a spiral disk is an effective mechanism for inducing radial inflow of gas toward the center of a galaxy. As a consequence of shocks and cloud-cloud collisions, gas piles up along the leading edges of the stellar bar (Roberts, Huntley, & van Albada 1979). The resulting asymmetric distribution of the gas with respect to that of the stars causes the latter to exert a gravitational torque on the former, thereby driving the gas inward. If the galaxy has inner Lindblad resonances (ILRs), the gas will collect between the inner and outer ILRs in the form of a ring-like configuration (see, e.g., Athanassoula 1992). This is an attractive way to supply gas to sustain the star formation activity observed in the central few hundred parsecs of many galaxies, since gravitational instability leading to cloud collapse may be an inevitable consequence of the accumulation of large amounts of neutral gas (Elmegreen 1994). Further inflow to smaller scales might proceed by a variety of pathways (e.g., Heller & Shlosman 1994; Wada & Habe 1992), although the detailed processes involved have yet to be thoroughly understood (Phinney 1994; Begelman 1994). Nevertheless, bar-driven inflow as a mechanism for the fueling of active galactic nuclei (AGNs) has been a popular idea (e.g., Simkin, Su, & Schwarz 1980; Shlosman, Frank, & Begelman 1989; Friedli & Benz 1993; Heller & Shlosman 1994).

2. OBSERVATIONS OF NUCLEAR STAR FORMATION

Thirty years ago, Sérsic & Pastoriza (1965, 1967) drew attention to the fact that galaxies containing ``peculiar'' or ``hot-spot'' nuclei are almost exclusively barred (but see the criticism by Heckman 1978). Using a small sample of galaxies having optical spectra, Heckman (1980) found that barred galaxies more frequently have nuclei showing signs of recent star formation. More evidence came from follow-up spectroscopic observations of objects selected from the Markarian surveys: both Huchra (1977) and Balzano (1983) found evidence for an excess of barred morphologies among starburst galaxies relative to the field galaxy population.

De Jong et al. (1984) noticed that optically-selected barred spirals tend to have higher infrared (IR) luminosities and hotter 100 to 60 μm colors (as measured by *IRAS*) than their unbarred counterparts. Similarly, Hawarden et al. (1986) discovered that more than one-third of barred spirals emit excess radiation at 25 μm; although the coarse *IRAS* beam could not constrain well the location of the emission within each galaxy, Hawarden et al. postulated that it emanates from circumnuclear regions with enhanced star formation. Puxley et al. (1987) confirmed through radio observations that the emission is confined mainly to the central 1-3 kpc. In a ground-based 10 μm survey of the central regions of IR-luminous galaxies, Devereux (1987) found that ~ 40% of *early-type* barred spirals have enhanced 10 μm emission. Devereux showed that the emission is compact ($\lesssim$ 1 kpc) and that these sources exhibit a 25 μm color excess ($S_{25\mu} / S_{12\mu} \gtrsim 2.5$) similar to that seen in the objects studied by Hawarden et al. (1986).

That the enhanced radiation in the centers of barred galaxies is powered predominantly by star formation and not nonstellar activity was demonstrated by Devereux (1989), who examined the published spectral classification of the objects in the 10 μm survey showing enhanced emission. Hummel et al. (1990) reached a similar conclusion for a sample of barred galaxies having enhanced radio continuum emission.

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3. OBSERVATIONS OF ACTIVE GALACTIC NUCLEI

The observational status of the effect of bars on AGNs is a bit more confusing. It is sometimes said in the literature (e.g., Shlosman et al. 1989) that all AGNs are barred; however, the evidence is far from clear. Adams (1977) and Simkin et al. (1980) first remarked that a large fraction of Seyfert galaxies contain morphological features such as rings and bars, suggesting that the latter might be instrumental in delivering fuel to the active nuclei. It must be remembered, however, that both of these early studies were based on rather small samples of galaxies, and that only a slight preponderance of barred host galaxies was suggested. Using a larger sample of objects, Arsenault (1989) reported an overabundance of barred galaxies with inner rings among H II nuclei *and* AGNs. However, as discussed in Ho, Filippenko, & Sargent (1996b), Arsenault's analysis is potentially flawed due to his particular choice of the control sample. Márquez (these proceedings) and Moles, Márquez, & Pérez (1995) did not find an excess of barred galaxies in a sample of AGNs selected from the Véron-Cetty & Véron (1991) catalog, although they suggested that there was an excess of inner rings among the subsample of AGNs lacking bars. It is difficult to assess the significance of the latter result without a proper control sample. As noted by Moles et al., contrary to the classification of bars, that of inner rings is not always consistently applied in the RC3 catalog (de Vaucouleurs et al. 1991). Moreover, unlike the case of most bars, the small linear size of inner rings makes their identification more dependent on angular resolution, and hence subject to more complicated selection effects.

A number of studies, albeit based on rather small samples, suggest that bars have an insignificant effect on AGNs (Heckman 1980; Fricke & Kollatschny 1989; MacKenty 1990). McLeod & Rieke (1995) examined the morphological properties of two samples of Seyfert galaxies - one distilled from the CfA redshift survey (Huchra & Burg 1992) and the other drawn from bright, nearby galaxies (Maiolino & Rieke, unpublished). They did not find an excess of barred galaxies in both samples. Tsvetanov (these proceedings) reported similar results from a sample of southern Seyferts. It has been argued (e.g., Shlosman, Begelman, & Frank 1990; Heckman 1992) that the fraction of barred galaxies may be underestimated in optical catalogs , as the effect of dust obscuration is strong and the old stellar population does not have a large contrast in visible light. Although near-IR imaging surveys sometimes do find previously unrecognized bars (e.g., Keel, Byrd, & Klaric, these proceedings), it seems quite clear that bars are *not* universally present in AGNs (McLeod & Rieke 1995).

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4. A NEW SURVEY

The recent completion of an optical spectroscopic survey of the nuclei of a large sample of nearby galaxies (Ho, Filippenko, & Sargent 1995) provides an excellent data base with which to reexamine the issues discussed above. High signal-to-noise ratio, moderate-resolution (2.5-4 Å), long-slit spectra were obtained for a magnitude-limited ($B_T \leq$ 12.5 mag) sample of 486 northern ($\delta > 0°$) galaxies using the Hale 5-m reflector at Palomar Observatory (Filippenko & Sargent 1985). Nearly all of the observations were obtained with a 2" slit, and spectra were derived from an effective aperture of 2" x 4", corresponding to physical dimensions of ~ 170 pc x 340 pc for the median distance of 17 Mpc.

Approximately 60% of S0-Sm spirals in our sample contain bars (Fig. 1), in agreement with the statistics of Sellwood & Wilkinson (1993) for field spirals. Adopting the spectral classifications given in Ho, Filippenko, & Sargent (1996b), we examine the dependence of the detection rate of H II nuclei (those photoionized by OB stars) and AGNs [including LINERs (low-ionization nuclear emission-line regions), LINER/H II nuclei transition objects, and Seyfert 1 and 2 nuclei] on the presence of a bar for 428 spiral galaxies. While the distribution of unbarred galaxies does not differ appreciably from that of barred galaxies among AGNs, there is clearly a difference among H II nuclei (Fig. 2). Applying the Kolmogorov-Smirnov test, we find that the probability (P_{KS}) that the two distributions are drawn from the same population is only 50.1% for the AGNs, whereas P_{KS} = 0.2% for the H II nuclei. The latter result is highly statistically significant, implying that nuclear star formation occurs more frequently in barred spirals.

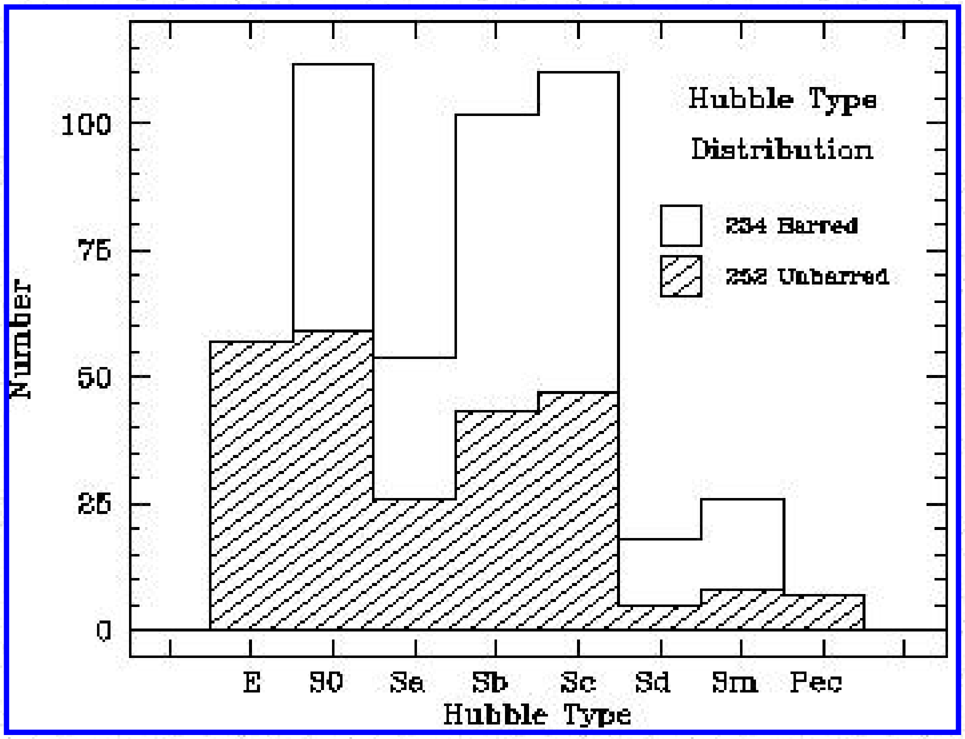

Figure 1. Distribution of Hubble types for the 486 galaxies in the survey. Unbarred galaxies are shown in the hatched histogram, and barred galaxies in the unhatched histogram.

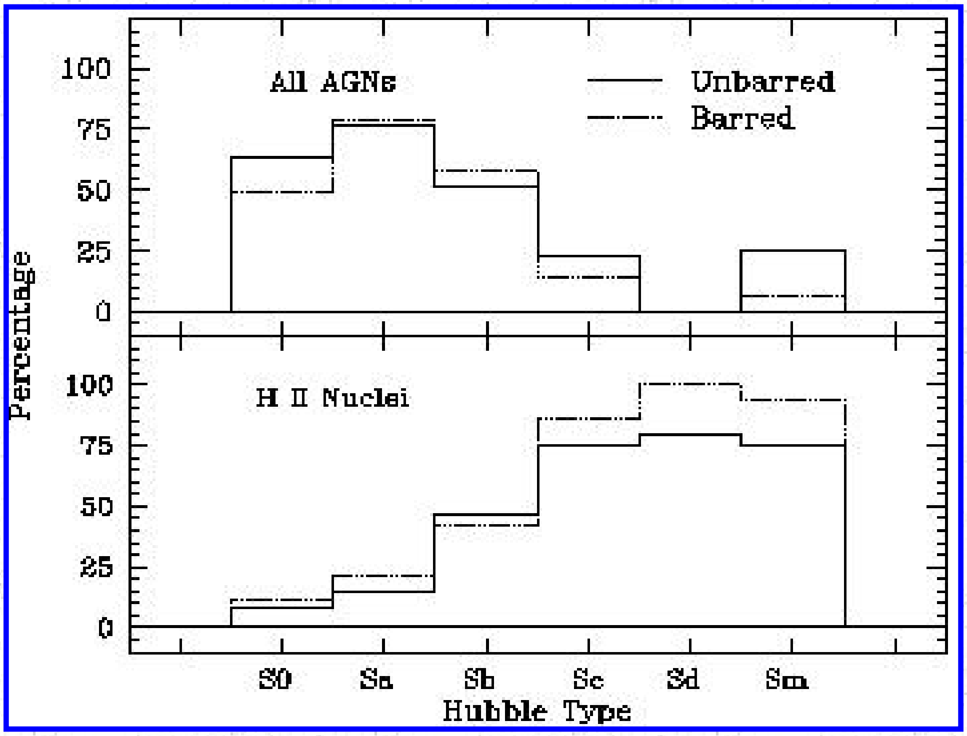

Figure 2. Distribution of AGNs (*top*) and H II nuclei (*bottom*) as a function of Hubble type. Barred and unbarred galaxies are shown separately.

The effect of bars on the *strength* of the activity can be gauged by inspecting the distributions of the luminosity of a strong emission line such as Hα. In Figure 3, ``early-type" spirals (S0-Sbc) are shown separately from ``late-type" spirals (Sc-Sm). It is apparent that among H II nuclei, barred early-type systems show significantly higher Hα luminosities than unbarred counterparts (P_{KS} = 3.3%), whereas no such trend is present for the late-type systems. The line strengths of AGNs, by contrast, appear not to be influenced by the presence of a bar, regardless of the morphological type. We find the same trend when we use the equivalent width of Hα emission as the indicator instead of the line luminosity (Ho et al. 1996c).

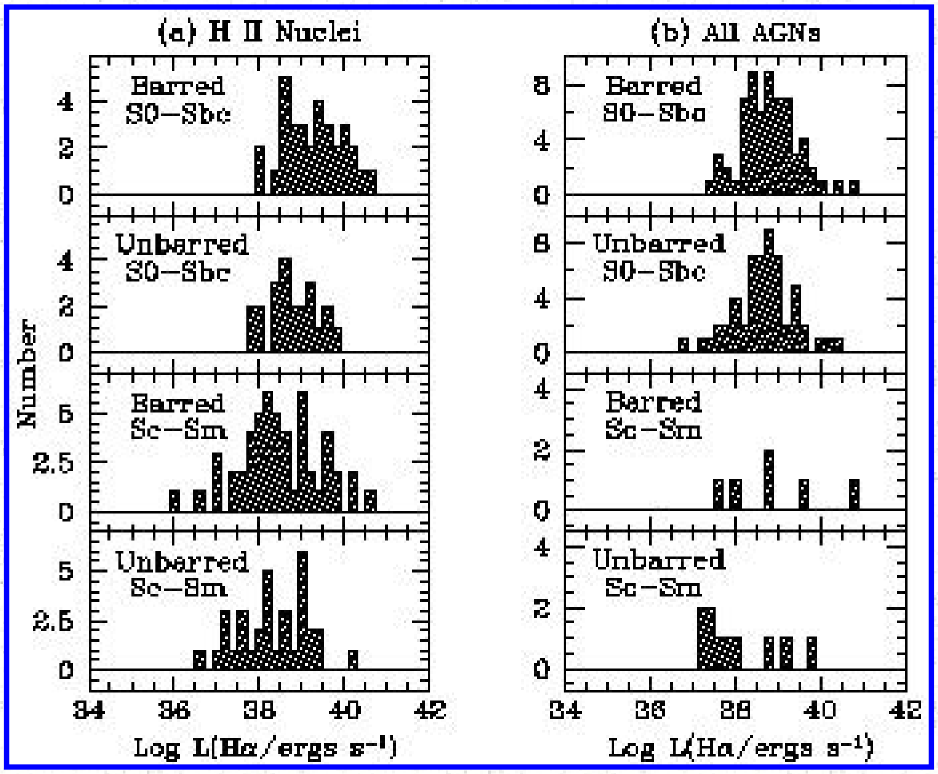

Figure 3. Distributions of Hα luminosities for (*a*) H II nuclei and (*b*) AGNs. The two top panels in each case show barred and unbarred for early-type (S0-Sbc) spirals, while the two bottom panels show late-type (Sc-Sm) spirals.

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5. CIRCUMNUCLEAR STAR FORMATION

The observations discussed in Sections 2 and 4 strongly suggest that the presence of a bar increases both the probability that a nucleus of an early-type spiral galaxy experiences star formation *and* the rate at which the stars form. By contrast, bars seem to have little influence on the global star formation properties of spirals (Kennicutt 1994). Insofar as numerical studies predict that the large-scale interstellar medium should be channeled to the central region of a barred galaxy, the observational evidence gives reassuring agreement. It should be stressed that star formation is a wide-spread phenomenon in the nuclei of both barred and unbarred galaxies (e.g., Ho et al. 1996b); the presence of a bar is neither a necessary nor a sufficient condition for nuclear star formation to take place. Undoubtedly, other factors such as the availability of gas must play a crucial role.

Interestingly, the enhancement of star-formation activity seems to take place preferentially in early-type spirals, confirming similar findings reported by Devereux (1987) and Dressel (1988) As noted by Devereux (1987), the dichotomy between the response of the gas to a bar in early and late-type spirals probably reflects the influence of the bulge-to-disk ratio on the rotation curve and on the relative positions of the primary resonances. If an ILR is present in an early-type disk, it is expected to be located interior to the bar and close to the nucleus; if a late-type disk contains an ILR, it will likely be found near the ends of the bar, whose extent is smaller than that of early-type systems (Elmegreen & Elmegreen 1985; Combes & Elmegreen 1993). Since the accretion rate depends on the length of the bar (Athanassoula 1992; Friedli & Benz 1993), it is natural to expect the most pronounced star-formation activity to occur in early-type systems.

Although the survey of Ho et al. (1995) lacks detailed two-dimensional information, narrow-band imaging studies (e.g., Phillips, these proceedings) indeed find that circumnuclear star formation appears to exist *only* in early-type spirals (Sb and earlier). In the few cases where high-resolution CO maps are available (e.g., Kenney et al. 1992), the ring-like distributions of the sites of recent star formation are roughly co-spatial with peaks in the molecular gas distributions, located near the expected position of the ILRs.

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6. FUELING OF NEARBY AGNs

The requirements for fueling AGNs are more stringent than those for fueling H II nuclei, since angular momentum transport must extend to much smaller radii. Numerical simulations (e.g., Heller & Shlosman 1994) show that a large-scale stellar bar can reduce the angular momentum of the gas only by a factor of ~ 10. A number of ideas have been suggested to further transport the gas to scales of interest for AGNs ($\lesssim$ 1 pc) (Lin, Pringle, & Rees 1988; Shlosman et al. 1989; Hernquist 1989; Pfenniger & Norman 1990; Wada & Habe 1992), with the ``bars-within-bars" mechanism originally proposed by Shlosman et al. (1989) being widely discussed.

The observations, however, seem to indicate that bars have a negligible influence both in the formation and/or fueling of nearby AGNs. Related to this is the obvious fact that in the general galaxy population the fraction of barred galaxies greatly exceeds that of Seyferts. Even when we include emission-line nuclei such as LINERs in the AGN census, barred galaxies still outnumber AGNs by a factor of two (Ho et al. 1996b).

If the proposed mechanisms of angular momentum transport operate in nature, they must do so rather inefficiently. A crucial element of the models which invoke gas dissipation to fuel the nucleus is that the gas must constitute a non-negligible fraction of the total dynamical mass. For example, in the ``bars-within-bars" models, the gas fraction amounts to ~ 10-20% of the total mass of the disk; likewise, the self-gravitating nuclear disk envisioned by Lin et al. (1988) requires a comparable amount of gas. Since AGNs occur predominantly in early- to intermediate-type hosts, perhaps the centers of these spirals lack sufficient gas for these mechanisms to ``kick in." Given that ILRs naturally develop in early-type barred galaxies (Combes & Elmegreen 1993) and that the initial large-scale radial inflow accumulates the gas between the inner and outer ILRs (Athanassoula 1992), it is conceivable that the region interior to the ILRs never attains a sufficiently high gas fraction. The gas content in the central ``cavity" in barred early-type galaxies may be low enough that the instability mechanisms proposed for further inflow cannot operate.

In a similar vein, one might appeal to a duty-cycle argument. Suppose that the inflow is not continuous, but rather episodic in nature, with the duration between episodes of accretion lasting on the order of the lifetime of the bar. The duty cycle may be related to the timescale for accumulating a critical amount of gas to initiate the instabilities required for the various mechanisms of radial transport. In the absence of conditions which lead to their destruction, bars appear to be long-lived structures (Sellwood & Wilkinson 1993). If the duty-cycle argument holds, it implies that fueling of nearby AGNs on nuclear dimensions must be a slow process.

A third possibility is that the very process of central accretion (or simply the presence of a massive black hole) and the concomitant development of a strong and extended ILR can also lead to the *destruction* of the bar (Hasan & Norman 1990; Pfenniger & Norman 1990; Friedli & Benz 1993). Such a regulating mechanism has been proposed by Friedli (1994) to account for the scarcity of luminous AGNs in the current epoch. Although this phenomenon may account for the similarity in the frequency of barred and unbarred AGNs, it does not explain why barred and unbarred AGNs currently show the same level of activity. Since the survivability of the bar depends sensitively on the mass of the central concentration relative to the mass of the stellar disk (Friedli 1994), this scenario can be tested by appropriate kinematic observations.

If gas from the kiloparsec-scale region is not the principal source of fuel in AGNs, is there a fuel crisis? To address this issue, let us consider the contribution of stellar sources alone. For an efficiency of conversion between matter and energy of $\varepsilon = 0.1$, the mass accretion rate required to sustain a luminosity L is $\dot{M} = (\varepsilon c^2)^{-1} L = 0.15(\varepsilon / 0.1) (L / 10^{45}$ ergs $s^{-1}) M_{\odot}$ yr^{-1}. While QSOs typically consume $\dot{M} \approx 10$-100 $M_{\odot}$ yr^{-1}, a rate which may be difficult to accommodate with stellar sources (Shlosman et al. 1990), a Seyfert nucleus such as that of NGC 1068 (Pier et al. 1994) only requires ~ 0.2 $M_{\odot}$ yr^{-1}, and the LINER nucleus in M81 just ~ 5×10^{-5} $M_{\odot}$ yr^{-1} (Ho, Filippenko, & Sargent 1996a). Fuel may be extracted from stars surrounding the nucleus from their tidal disruption by the central massive black hole (e.g., Hill 1975; Rees 1988; Roos 1992). According to Eracleous, Livio, & Binette (1995), one could expect a stellar disruption once every 100-200 years for a black hole mass of 10^6-10^7 $M_{\odot}$; the tidal debris forms an elliptical accretion disk capable of sustaining the ionizing radiation of low-luminosity sources for several decades. Another source of fuel is expected from the normal mass loss of stars in the vicinity of the nucleus. Ho et al. (1996c) show that if galaxy nuclei have sufficiently high stellar densities, as seems to be the case for some objects recently imaged by the *Hubble Space Telescope*, an appreciable amount of material is available to sustain the feeble power in nearby AGNs.

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