PREPRINTS

of the

STEWARD OBSERVATORY

THE UNIVERSITY OF ARIZONA
TUCSON, ARIZONA 85721 U.S.A.

No. 1177

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To Appear in Violent Star Formation from 30 Doradus to QSOs,
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Stellar Ionization of Low-Luminosity Active Galactic Nuclei

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Low-Ionisation Nuclear Emission-Line Regions (LINERs) are a common constituent of galaxies, and are often regarded as a weak form of Seyfert activity. LINERs have emission-line luminosities that are similar to those of giant H II regions, however, and recent theoretical work suggests that their nebular properties can be reproduced in many cases with photoionisation by normal O stars. In an extension of this scenario, energetic phenomena such as nonthermal radio emission, broad Hα features, and substantial X-ray luminosity seen in some LINERs might be attributable to supernovae. In this review I consider the empirical evidence bearing on an interpretation of LINERs as stellar-powered sources. While stellar phenomena appear capable of matching LINERs of modest luminosity in terms of broad-band energetics, some important differences remain in detailed spectral characteristics, particularly at X-ray energies. A certain amount of anomalous behavior on the part of stars within galaxy nuclei (e.g., in terms of the initial mass function) is required if LINERs result from stellar ionisation.

1. Introduction

Spectroscopic surveys indicate that $\sim$ 30% or more of bright galaxies contain weak emission-line nuclei that are classified as LINERs (Low-Ionization Nuclear Emission-Line Regions; Heckman 1980b, hereafter H80b). The intensity ratios of low-ionization optical lines relative to recombination features are characteristically higher in LINERs than in H II regions, causing LINERs to be regarded as "active" nuclei subject to unusual energetic processes. The luminosities of LINERs and giant H II regions are comparable, however, with typical Hα luminosity $\sim 10^{40}$ erg s^{-1} or somewhat less. This fundamental resemblance provides motivation for examining the possibility that LINERs and H II regions are actually powered by a common energy source, namely a population of hot stars. Under this scenario, the observational distinctions between LINERs and giant H II regions must be accounted for in terms of differences in the associated stellar populations and/or in the properties of the nebular gas.

This contribution will review evidence supporting and opposing an interpretation of LINERs as the products of stellar ionization. The conjecture that LINERs are ultimately stellar phenomena is closely related to work by Roberto Terlevich and collaborators that interprets active galactic nuclei (AGNs) more generally as anomalous starbursts. The starburst-AGN scenario has been criticized on the basis of the requisite (high) efficiencies of broad-band energy generation (e.g., Heckman 1989), but these arguments are largely obviated when only low-luminosity nuclei are considered. LINERs differ from Seyfert nuclei and QSOs in terms of their optical and X-ray characteristics as well as typical luminosity, and hence it may be physically meaningful to consider LINERs apart from the remainder of active nuclei, as stellar-ionized sources. For purposes of this discussion, LINERs are defined according to criteria suggested by H80b, such that oxygen line intensities are in a proportion of ([O III] λ5007 : [O II] λ3727 : [O I] λ6300) = (1 : > 1 : > 0.3). A Hubble constant of $H_0 = 75$ km s^{-1} Mpc^{-1} is assumed throughout this review.

2. LINER Ionization Mechanisms

Several mechanisms are capable of generating plasma with the ionization and thermal conditions necessary for producing LINER-like emission. The general requirement is gas described at least in part by densities $n_e \lesssim 10^3$ cm^{-3} (dictated by the critical densities of the [O II] λ3727 and [S II] λ6724 line pairs), subject to weak ionization, while maintaining a rather hot electron population responsible for collisional excitation and resultant forbidden-line emission. Shocks with velocities of order ~100 km s^{-1} provide one mechanism for generating such plasma (e.g., Shull & McKee 1979). Shocks associated with large-scale winds appear to be responsible for LINER-like emission observed in some starbursting galaxies (Heckman *et al.* 1990). Photoionization can also generate LINER nebulosity (Ferland & Netzer 1983; Halpern & Steiner 1983). Successful photoionization models require a low ionization parameter (U; ratio of ionizing photon to nucleon density) compared to that describing H II regions and Seyfert nuclei; in addition, the ionizing continuum must be relatively hard in order that the heating per ionization be large enough to produce strong forbidden-line emission. LINER-like emission is seen in the central galaxies of X-ray cooling-flow clusters (Heckman *et al.* 1989 and references therein). This nebulosity is probably generated by photoionization by the cooling intracluster plasma (Donahue & Voit 1991) or by energy transfer in turbulent mixing layers at the interface of the hot and warm media (Begelman & Fabian 1990).

This review will focus on compact nuclear sources of LINER emission, which constitute the most common manifestation of such nebulosity. This selection avoids most cases in which the nebular gas is powered by starburst winds or cluster cooling flows. The relative role of shocks and photoionization for energizing compact LINERs remains ambiguous, however. A number of LINERs resemble Seyfert nuclei by exhibiting significant X-ray luminosity and a broad component to Hα. Strong evidence exists (e.g., correlated continuum and line variations) implying that Seyferts are primarily photoionized. By extension, it can thus be argued that compact LINERs are similarly dominated by photoionization. This argument is plausible but not robust; for example, photoionization may only dominate the weak broad-line components of LINERs, while the narrow-line emission could be generated largely in shocks.

Observational diagnostics of the ionization mechanism in LINERs, such as the [O III] temperature or ratios of oxygen and sulfur lines, have been confounded by density effects and other ambiguities (e.g., Filippenko & Halpern 1984; Kirhakos & Phillips 1989). It is also unclear whether existing shock models satisfactorily account for the detailed emission spectra of real shocks (e.g., see Ho *et al.* 1993 for a discussion). In my view, the importance of shocks in generating LINERs remains an open question that is in danger of being neglected. The increasing emphasis on photoionization and neglect of shocks stems at least in part from the lack of a well-defined geometrical picture of how shocks are produced and sustained in a galaxy nucleus. With this caveat in mind, the remainder of this discussion will nonetheless emphasize photoionization processes for generating most of the optical emission.

As noted above, several observational characteristics suggest continuity in the properties of LINERs and Seyfert nuclei. These features include X-ray emission, which for LINERs is seen in ~ 10 objects to date. X-ray luminosities range from a few times 10^{40} erg s^{-1} (e.g., M81; Petre *et al.* 1993) to more than 10^{43} erg s^{-1} (Pictor A; Singh *et al.* 1990); values near the lower end of this range (~ 10^{41} erg s^{-1}) seem typical. There is some tendency for LINERs detected as X-ray sources to exhibit other signs of Seyfert-like activity, including weak emission of broad Hα or of high-ionization lines (e.g., [Ne V] λ3426), or relatively strong nonthermal radio emission; in this sense, X-ray-detected sources may be more "active" overall than the majority of LINERs. Broad Hα emission, which is a hallmark of Seyfert 1 activity, is seen more generally in an important fraction of LINERs (Filippenko & Sargent 1985). Optically identified LINERs tend to be associated with weak, AGN-like, nonthermal radio cores, with 5 GHz luminosities of $\lesssim 10^{27}$ erg s^{-1} Hz^{-1} (H80b). LINERs as well as Seyferts preferentially occur in early-type galaxies (H80b). Finally, both LINERs and Seyfert nuclei often show a correlation between forbidden-line velocity width and critical density (e.g., Pelat *et al.* 1981; Filippenko & Halpern 1984). The last correlation implies that these nuclei are structured in such a way that plasma moving at the highest velocities also tends to be described by the highest densities. In light of these similarities, it is understandable that LINERs are often viewed as diminutive forms of Seyfert/QSO activity.

Significant continuity also exists between the properties of LINERs and H II nuclei, however. By H II nuclei, I refer simply to emission-line nuclei of galaxies that spectroscopically resemble H II regions in other environments. H II nuclei are presumably powered by normal O stars, although these nebulae exhibit some peculiarities relative to typical disk H II regions (Kennicutt *et al.* 1989, hereafter KKB). LINERs and H II nuclei are similar in Hα luminosity (Heckman 1980a,b; H II nuclei may actually be slightly *more* luminous on average, cf. Hummel *et al.* 1990). The nebular gas in both types of nucleus tends to be characteristically denser and probably more highly clumped than in typical H II regions (KKB; Filippenko & Halpern 1984). H II nuclei and (to a greater degree) LINERs both exhibit elevated [S II] and [N II] line strengths that are not easily interpreted as simply signatures of enhanced heavy element abundances in otherwise normal H II regions (KKB). Both classes of nuclei also exhibit Hα/radio continuum ratios that are low by an order of magnitude compared with that typical of disk H II regions. For the H II nuclei, the difference is unlikely to be entirely due to extinction of Hα; an extra nonthermal radio component is apparently present in many of these nuclei, as well as in LINERs.

The peculiarities of H II nuclei are open to several interpretations. KKB suggested that essentially all emission-line nuclei contain an AGN that is presumably nonstellar. In low-luminosity sources, the AGN produces LINER-like emission. H II nuclei are then composite sources in which a weak LINER and circumnuclear H II regions are spatially unresolved in the observations; the AGN is thus responsible for any anomalies. The nuclei of galaxies are unusual environments for reasons other than the putative presence of a massive black hole, however, and some of these other aspects may influence the character of the emergent radiation. Galaxy nuclei tend to be metal-rich in comparison to extranuclear sites. Observational evidence exists suggesting that the interstellar dust within galaxy nuclei is unusual, probably in the sense of having larger characteristic grain size (Laor & Draine 1993; Lauer *et al.* 1993). As the center of a galaxy's potential well, the nucleus is likely to be subject to unusually high interstellar pressures and densities. Pressures that are 2 orders of magnitude or more higher than for our local interstellar medium have been established observationally for the centers of some early-type galaxies (Thomas *et al.* 1986) and of the Milky Way (Spergel & Blitz 1992). Gas within the nuclei of galaxies may also be subject generally to an unusual degree of shear and turbulence, as is the case for the Galactic center (Güsten *et al.* 1987). All of these characteristics may be important for modifying the emission of nebular gas located in such an environment.

3. Stellar Ionization of LINERs

3.1. *Theoretical Picture*

If LINERs are ionized by stars, the effective temperature T_{eff} of the stars must be fairly high. Terlevich & Melnick (1985) proposed that massive stars forming in galaxy nuclei would experience enhanced mass loss and stripping due to their high metallicity, and would subsequently evolve into extreme Wolf-Rayet sources that they labeled "Warmers." Using stellar evolution and atmosphere models then available, Terlevich & Melnick argued that the composite spectrum of a population of Warmers and unevolved O stars would resemble a power-law through the extreme ultraviolet bandpass. This ionizing spectral energy distribution meets the requirements for photoionization of LINERs and more luminous AGNs, thus providing the basis for the starburst-AGN theory as originally framed.

The high metallicities required for production of Warmers are apparently not attained outside of galaxy nuclei, making the existence of Warmers difficult to test empirically. In a reanalysis of the Warmer problem, Leitherer *et al.* (1992) repeated the calculations of Terlevich & Melnick using updated stellar evolution and atmosphere models. Use of the new models results in a significantly softer ionizing continuum for a stellar population expected in galaxy nuclei. These results cast doubt on whether Warmers are important sources of ionizing radiation within AGNs. (In the more recent incarnations of the starburst-AGN model, supernovae actually play a more important role than Warmers in generating the observed emission; see, e.g., Terlevich *et al.* 1992.) While the existence of Warmers as originally envisioned is thus in question, in resolving this issue we remain dependent on the stellar modelers. Recent stellar evolution and atmosphere calculations presumably represent improvements over older work, yet it remains possible that an enlarged role for Warmers may reemerge in future predictions as more physics is included in the models.

Recent photoionization calculations suggest that the optical emission-line characteristics of many LINERs can actually be reproduced through photoionization by *normal* O stars (Filippenko & Terlevich 1992; Shields 1992). This scenario requires fairly hot stars ($T_{eff} \gtrsim 45,000$ K), and in addition, a reduction in U by an order of magnitude from that characteristic of normal H II regions, for at least a part of the irradiated plasma. The high interstellar densities expected and measured for galaxy nuclei may provide a natural means for reducing U, which will be inversely related to n_e for a fixed radiation field. The best match to observed LINER spectra results if the nebular gas is described by a range of n_e and U, since the emissivity in different lines will be maximized under different conditions. Emission in high critical-density transitions is enhanced in high density gas, since collisional quenching of low critical-density cooling transitions (particularly infrared fine-structure lines) leads to a higher nebular temperature and greater excitation.

If LINERs are the product of hot stars in dense gas, we can make qualitative sense of several patterns of nuclear emission in terms of a picture in which large galaxy bulges are described by deep central potentials resulting in high central gas pressures and densities. Among these trends is a tendency for low-luminosity nuclear emission in early-type galaxies to appear LINER-like, while late-type galaxies tend to host H II nuclei (H80b). Among early-type galaxies alone, nuclear emission regions in large galaxies are usually LINERs, while small galaxies feature H II-region emission (Phillips *et al.* 1986). There is also some tendency for the size of nuclear emission regions to increase from early to late Hubble types (Pogge 1989); a similar pattern is seen in the dimensions of nuclear radio sources (Giuricin *et al.* 1990; Hummel *et al.* 1990). In terms of the simple scenario considered here, the variation of nebular size reflects the dependence of Strömgren depth on density, while the same trend in radio dimensions results from increased confinement of the nonthermal plasma in denser environs. Finally, recent observations indicate that the nuclear J, H, K-band (stellar) luminosity is larger in LINERs than in H II nuclei, independent of galaxy luminosity and Hubble type (Giuricin *et al.* 1993). This trend again may be indicative of deeper central potentials for the LINERs.

3.2. *Direct Evidence for Hot Stars*

If LINERs are powered by hot stars, we might hope to see signatures of a young population in the stellar continuum of these nuclei. At optical wavelengths, some LINERs do show significant Balmer absorption indicative of intermediate spectral-type (B − A) stars, although this is not the case for the majority of sources (e.g., Heckman 1980a). The absence of these features may require that star formation within nuclei be described by an unusually shallow initial mass function (IMF) if LINER emission is stellar-generated, although the quantitative comparisons needed to make this statement have not been done.

Terlevich *et al.* (1990) have argued that large near-infrared Ca II absorption equivalent widths observed in Seyfert nuclei are probably indicative of a population of young red supergiants. Measured EW(Ca II) in such objects is inconsistent with simple dilution of a normal galaxy spectrum by a power-law continuum inferred from absorption features at shorter wavelengths. Similar Ca II equivalent widths are observed in LINERs (Terlevich et al. 1990); however, little evidence is seen for dilution of *any* stellar features in most LINERs. Ca II equivalent widths in LINERs are consistent with those of normal galaxy nuclei. In early-type galaxies of the sort that typically host LINERs, nuclear EW(Ca II) also appears to connect fairly smoothly to gradients in this feature observed at larger radii, which probably reflect average stellar metallicity as a function of radius (Delisle & Hardy 1992).

The ultraviolet bandpass is likely to be the best place to hunt for evidence of young stars in nuclei, due to the relatively high contrast between young and old populations in this wavelength interval. Ultraviolet spectra from *IUE* exist for over a dozen LINERs, and in a few cases show evidence for hot stars (Goodrich & Keel 1986; Reichert *et al.* 1993). In general, however, the data quality is limited, and upper bounds to hot star numbers are relatively weak, particularly when possible extinction is considered. Evidence for a power-law continuum through the UV region in LINERs is also somewhat ambiguous (Fosbury *et al.* 1981; Bruzual A. *et al.* 1982). Elliptical galaxies commonly show a rise in the continuum shortward of $\sim$ 2000 Å (Burstein *et al.* 1988), but this light probably originates in a population of evolved stars that contributes little ionizing radiation ($T_{eff} \lesssim 30,000$ K; Ferguson & Davidsen 1993).

3.3. *Hot Stars in Metal-Rich Environments*

The scenario for stellar ionization of LINERs outlined in §3.1 is not without potential problems, including the necessity of early O stars in relatively enriched centers of galaxies. Studies of H II regions in disk environments reveal an inverse relation between metallicity and T_{eff} of the ionizing stars, where both quantities are inferred from the strengths of nebular lines (e.g., McCall *et al.* 1985). At metallicities of solar levels or higher expected for galaxy nuclei, ionizing stars with $T_{eff} \gtrsim 45,000$ K are unexpected on the basis of this trend. The physical origin of the correlation for H II regions is poorly understood. One possible explanation is that the ionizing radiation emergent from the most massive stars is systematically softened by changes in stellar structure, atmospheres, or winds accompanying increases in metallicity. The latest generation of stellar evolution calculations appears to support this interpretation; see discussions by McGaugh (1991) and García

Vargas (this conference). This conclusion is again only as robust as the current stellar models, however.

An alternative explanation is that the IMF for star formation responds to metallicity in such a way that fewer high mass stars form in enriched media (e.g., Shields & Tinsley 1976). The physical basis for this behavior may lie, for example, in the role of heavy elements in cooling pre-stellar gas clouds, which could lead to more efficient fragmentation and collapse, and hence less massive stars, when abundances are high. If variations in the IMF are important in producing the observed metallicity–T_{eff} relation, star-forming regions in galaxy nuclei might deviate from this trend if other factors influence the IMF in these locales.

Star formation biased to high masses is not an altogether *ad hoc* proposition for galaxy nuclei. Shearing and turbulent cloud motions could suppress low-mass star formation requiring a quiescent environment, while high densities and violent compression resulting from cloud collisions could facilitate collapse of large masses; this physical scenario is qualitatively consistent with the picture of star formation mediated by magnetic field strength discussed by Shu *et al.* (1987). Some empirical encouragement for invoking modifications to the IMF in LINERs might be taken from results presented at this meeting by E. Malumuth, which show that the highly compact stellar core of 30 Doradus is described by a relatively flat high-mass IMF compared with standard IMFs or that measured for the remainder of the H II region. If the relevant physical conditions of the 30 Dor core are replicated in galaxy nuclei, preferential formation of high-mass stars would not be surprising.

4. Energetic Phenomena and Supernovae

Normal stars *per se* do not provide a simple explanation for Seyfert-like signatures – broad Hα, nonthermal radio emission, significant X-ray luminosity, high-ionization lines – found in some LINERs. An extra ingredient must be invoked, and one possibility consistent with stellar ionization is the supernovae (SNe) that will result from a population of young stars. This explanation is essentially the same as is employed in the starburst-AGN model, although by limiting our view to low-luminosity sources we can again avoid many possible objections and utilize known astronomical entities with less extrapolation into unknown physical regimes.

4.1. *Theoretical Picture*

The stellar explosions that empirically come closest to producing the requisite features of LINERs are a class of radio-loud Type II SNe (Weiler *et al.* 1986). Broad Hα emission is a general characteristic of Type II SNe, but only a small fraction of these events are strong radio sources. The radio emission is interpreted as synchrotron emission generated in an interaction between the expanding SN and dense circumstellar material deposited by a wind from the progenitor star (Chevalier 1981, 1982). Terlevich *et al.* (1992) have argued that such SNe should be the norm in galaxy nuclei since dense interstellar gas will tend to confine wind ejecta to a dense shell.

The supernova ejecta and circumstellar material that have been shocked will both emit thermal X-rays, with the supernova plasma dominating at soft energies, while the circumstellar matter will radiate most of its energy in photons as hard as 100 keV. The cooler supernova gas is expected to dominate the X-ray spectrum, although the detailed proportions depend on density structure in the supernova shell and the wind. Increasing the circumstellar density is expected to increase emission at both radio and X-ray energies, thus providing a theoretical escape if extranuclear SNe that we observe are somewhat underluminous compared to the galaxy nuclei. While higher circumstellar densities may be the norm for evolved stars in galaxy nuclei, the stellar-ionized scenario would obviously be more satisfying if SNe are found that match LINER characteristics without theoretical mediation.

4.2. *Empirical Comparisons*

Extranuclear radio-loud supernovae are rare events, and only a small number of examples have sufficient observations to provide useful comparisons with LINER properties. While a SN can outshine its host galaxy near maximum light, the duration of this peak in output is expected to be considerably shorter than the interval between SN explosions in LINER nuclei (§4.2.4). As a consequence, the most recent SN seen in a stellar-ionized LINER should, on average, be in an early remnant phase. In the following empirical comparisons I will consequently emphasize late-time observations of modern SNe. The detailed consistency of using SNe to explain high energy phenomena in LINERs requires additional consideration of the temporal behavior of SNe, as discussed in §4.2.4.

4.2.1. *Radio Emission*

The SNe of interest emit nonthermal radio emission with 5 GHz luminosities of up to $\sim 10^{27}-10^{28}$ erg s^{-1} Hz^{-1} at peak brightness (typically within a few years post-explosion; Weiler *et al.* 1986 and 1990), which is in good agreement with LINER luminosities. The radio spectra of the SNe are inverted ($\alpha > 0, f_\nu \propto \nu^{+\alpha}$) at low frequencies at early times, with a turnover to $\alpha < 0$ above a transition frequency that decreases with time. This behavior is interpreted in terms of time-dependent free-free absorption by circumstellar material. The spectral index at late times is typically ~ -0.6; the resulting range in spectral index is generally consistent with spectral slopes found for LINERs (e.g., Heckman *et al.* 1980).

A minority of LINERs are considerably more powerful radio sources with extended, double-lobed radio morphologies (e.g., Pictor A; Jones & McAdam 1992 and references therein); it seems highly unlikely that the radio luminosity of these sources can originate in normal stellar phenomena.

4.2.2. *Optical Emission*

Near maximum light, the optical spectra of Type II SNe are dominated by broad emission in hydrogen Balmer lines. Three radio-loud Type II SNe have been detected in Hα at much later times: SN 1970G (Fesen 1993), SN 1979C (Fesen & Matonick 1993), and SN 1980K (Fesen & Becker 1990; Leibundgut *et al.* 1991), observed 22, 12, and 8 years post-explosion, respectively. All three exhibited Hα in emission with full-width near zero intensity in excess of 10,000 km s^{-1}, which is comparable to Hα widths seen in LINERs. The luminosity of broad Hα for the three SNe was $10^{37} - 10^{38}$ erg s^{-1}, with no simple dependence on remnant age. While quantitative estimates of broad Hα luminosity for LINERs are sparse (due to the difficulties of deblending this component) and biased to high-luminosity sources, available numbers tend to be at least somewhat higher than the SNe values. M81, for example, emits at least 5×10^{38} erg s^{-1} in broad Hα (Filippenko & Sargent 1988), which lies at the lower end of quantitative measurements. Better information on typical LINER Hα luminosities that is appropriate for this comparison will soon be available from the Palomar Observatory Dwarf Seyfert Survey (Filippenko & Sargent 1985; Ho *et al.* 1994). A potentially more serious problem with invoking SNe to explain high-velocity LINER features is that the broad Hα seen in the SN prototypes considered here is accompanied by [O I] $\lambda\lambda$6300, 6364 emission of comparable width and luminosity. Such a feature has never been reported in the spectra of LINERs or other AGNs.

Slightly higher Hα luminosity ($\sim 4 \times 10^{38}$ erg s^{-1}) and relatively weak [O I] have been seen in two other radio-loud SNe observed at late times: SN 1978K (Ryder *et al.* 1993) and SN 1986J (Leibundgut *et al.* 1991), for which optical spectra were obtained approximately 12 and 7 years post-explosion, respectively. The interpretation of these sources is complicated by a lack of spectra near maximum light permitting classification by standard means. While representing improvements in some sense for matching LINERs, SN 1978K and SN 1986J emit significantly narrower Hα (full-width at half-maximum of 560 and 1700 km s^{-1}, respectively) that is likely to be inadequate for explaining the broad features observed in galaxy nuclei (e.g., M 81 displays broad Hα FWHM = 2200 km s^{-1}; Filippenko & Sargent 1988).

4.2.3. *X-ray Emission*

A relatively new observational development is the detection of these last two SNe – SN 1978K (Ryder *et al.* 1993) and SN1986J (Bregman & Pildis 1992) – as X-ray sources approximately 13 and 9 years post-explosion, respectively. Both objects exhibited 0.1 – 2.5 keV luminosities of $\sim 10^{40}$ erg s^{-1}, which is comparable to the lower end of detected LINER luminosities. Spectroscopically, however, these SNe differ significantly in X-ray properties from the galaxy nuclei. When fit by a power law over a bandpass of 0.1 – 2.5 keV, the spectrum of SN1986J is described by a spectral index of $\alpha = -2.1$ (although a thermal continuum provides a somewhat better fit; J. Bregman 1993, private communication). SN1978K shows a considerably steeper X-ray continuum, with $\alpha = -4.5$ (Ryder *et al.* 1993). Both slopes are significantly steeper than the average for LINERs of $\alpha \approx -1.0$ (Mushotzky 1993).

4.2.4. *Temporal and Statistical Consistency*

The comparisons given above demonstrate that known SNe come close to replicating some general high-energy characteristics of LINERs, although important discrepancies remain in the details. The value of these comparisons is limited by the small number of sources on which they are based. Additional optical and X-ray data for radio-loud supernovae, as well as quantitative measures of broad Hα and X-ray emission in LINERs, would help to define what "typical" behavior is for both types of object. Even if a subset of supernovae is observed to reproduce LINER-like properties in luminosity and spectral detail, good statistics for the LINERs and temporal information for the SNe will be necessary to demonstrate that the duty cycle for observable SN features is consistent with the incidence of high-energy features in LINERs. A simple calculation using approximate numbers illustrates how the latter comparison would proceed. If we suppose that a typical LINER has a (narrow) Hα luminosity of $\sim 10^{40}$ erg s^{-1}, powering this nebula would require $\sim 10^3$ O stars. Since the lifetime of an O star is of order 10^7 yrs, in a steady state we would then expect a LINER to produce 1 SN every 10^4 yrs, on average. If 10% of LINERs exhibit a broad Hα component, then a SN must be capable of sustaining a corresponding luminosity in broad Hα for $\sim$ 1000 yrs. A duration of this length may exceed that permitted by reasonable thermalization efficiencies; however, a shorter timescale might result from more accurate numbers and consideration of IMF effects in relating ionizing luminosity to SN rate. Analogous calculations could be done for radio and X-ray emission.

At late times, SNe generally evolve slowly in their spectral properties. However, observations of a LINER bracketing a nuclear SN explosion in time would be expected to show significant temporal variation. Very limited information is available for variability of sources with the low powers typical of LINERs. Relatively detailed observations exist available for NGC 4278, which brightened by $\sim 70\%$ at 5 GHz between 1980 and 1985 to reach a maximum luminosity of $\sim 4 \times 10^{28}$ erg s^{-1} (Wrobel & Heeschen 1991), and subsequently began to decline in power. Comparison of the radio spectra in 1980 and 1985 shows a greater brightening at higher frequencies, which is qualitatively consistent with addition of a SN that is initially optically thick to free-free absorption at low frequency. Detailed modeling would be necessary to see if the quantitative behavior and timescales for the radio variations are consistent with a SN interpretation. At late times, radio luminosity from SNe is usually observed to decay with a power-law dependence on time (typically $t^{-0.7}$; Weiler *et al.* 1986). More complicated temporal variation in luminosity and spectral shape can result from structure in the circumstellar medium (Weiler et al. 1990 and 1992).

Strong optical variability has been seen in one LINER, NGC 1097, which changed over a few years from having no detectable broad Balmer emission to showing strong, broad features at both Hβ and Hα (Storchi-Bergmann *et al.* 1993). The broad emission is noteworthy for having a double-peaked profile similar to Balmer features in other AGNs that have been interpreted as a product of an accretion disk or jets. Double-peaked profiles have not been observed in the spectra of SNe, although the broad Hα profiles in late-time SN spectra are sometimes notably boxy (e.g., Fesen 1993).

NGC 1097 has a compact nonthermal radio core with 5 GHz luminosity of $\sim 10^{27}$ erg s^{-1} Hz^{-1} (Hummel *et al.* 1987), which is typical of LINERs. The galaxy also emits an X-ray luminosity within 0.2 – 4.0 keV of 1.1×10^{41} erg s^{-1} (Fabbiano *et al.* 1992, based on measurements in 1979). The narrow-line fluxes quoted by Storchi-Bergmann *et al.* are actually inconsistent with classification of NGC 1097 as a LINER, if we stick to the current definition (§1), and are perhaps in better agreement with a Seyfert 2 designation. However, observations of the same object by Phillips *et al.* (1984) are fully consistent with a LINER classification. The narrow emission-line equivalent widths in NGC 1097 are small, and discrepancies between the two studies are probably traceable to slight differences in subtraction of the stellar continuum or the use of slightly different measurement apertures. Whether a specific choice of classification in this case is physically meaningful for our purposes is open to question.

X-ray variability on timescales of years is well documented for several LINERs (Mushotzky 1994). One LINER, M81, has also exhibited rapid X-ray variability on timescales of minutes (Barr *et al.* 1985), and such behavior is often taken as evidence in support of the black hole paradigm for AGNs. Terlevich *et al.* (in preparation) have argued that fast shocks in dense, clumpy SN ejecta could give rise to this kind of variability. No variability on short timescales has been reported in the very limited X-ray data for SNe.

5. Summary and Future Prospects

The preceding observational comparison demonstrates reasonable agreement between a number of LINER properties and stellar-powered phenomena in terms of overall energetics, but important differences remain between detailed aspects of the spectral energy distribution for the two source types. A model in which LINERs are powered by stellar phenomena evidently still requires a certain amount of anomalous behavior on the part of stars inhabiting galaxy nuclei. The mismatch of empirical properties and the speculative character of stellar-powered LINERs might both be reduced by additional observational and theoretical work.

The kind of observations that are desirable for this purpose are mostly obvious. Supernovae observed to date show characteristic patterns of radio spectral evolution, and it would be of interest to see if similar behavior occurs in LINERs. LINER variability data at all wavelengths would be valuable more generally for understanding the origins of nuclear activity in these sources. Such observations have utility beyond comparison with SNe, and may allow tests of other physical scenarios and paradigms.

Improved and more extensive ultraviolet spectroscopy of LINERs using the *Hubble Space Telescope* would help to place direct constraints on the presence of hot stars or a featureless continuum, and would also provide nebular diagnostics of the continuum shape. Imaging of LINERs with *HST* would also be of interest for constraining the size of the nuclear source; an example already exists in the case of M 81, in which the nuclear Hβ emission region is smaller than 0.12 pc (Crane *et al.* 1993). A size this small does not preclude generation of the LINER by stars – 30 Doradus and probably M 33 (which does not have a nuclear black hole with mass in excess of 5×10^4 $M_\odot$; Kormendy & McClure 1993) have stellar cores that are smaller. However, such measurements place potentially interesting constraints on the physical characteristics of a nuclear star-formation environment.

Additional X-ray studies of LINERs and SNe would be informative, and data at relatively hard energies (as can be obtained with *ASCA*) are likely to be the most useful for testing the stellar-ionized LINER scenario. Both classes of object deserve additional X-ray study on their own merits, apart from the current comparison. For SNe, the X-ray behavior provides a probe of the circumstellar environment and blast-wave physics; for LINERs, the relationship to more luminous AGNs at X-ray wavelengths needs further study. A potential pitfall for future X-ray studies of LINERs that push to fainter luminosities is confusion with normal X-ray binaries; M 33, for example, has a nuclear X-ray luminosity of $\sim 10^{39}$ erg s^{-1} that might best be explained by a small number of stellar binaries (Hernquist *et al.* 1991).

Several avenues also exist for advancing the understanding of LINERs through theoretical work and new approaches to data analysis. Hubble type morphology provides only an approximate measure of more fundamental physical parameters of galaxies. The role of cloud density in influencing nuclear emission characteristics would be better tested by the extent to which direct measures of central potential well depth – such as pressure (inferred from X-ray data) or stellar velocity dispersion – provide sequencing parameters for LINER versus H II nucleus behavior. Comparable work has already been attempted using stellar metallicity as a fundamental parameter (Bonatto *et al.* 1989).

Additional thought should also be given to the structure and geometry of nuclear nebulae. Ionizing stars located in very dense interstellar environments are known in our own Galaxy, and are identified as ultracompact H II regions. These sources are not observed as LINERs, and in fact, are generally undetected optically because they are so heavily embedded. If stars (or accreting black holes) in dense media generate LINERs, the nebular structure must be modified in such a way that coverage is reduced. Violent gas motions within galaxy nuclei might be involved. Within our own Galactic nucleus, the nebular gas within the central parsec is arranged in an apparent ring that is probably photoionized by stars residing within a central cavity (e.g., Jackson *et al.* 1993); the geometry is far from being a simple Strömgren sphere. Issues of geometry are also important for progress in understanding the role of shocks in generating compact LINERs.

The correlation of critical density with velocity width for nebular features in LINERs is providing important information on nuclear structure, although it remains subject to ambiguity. In the accreting black-hole paradigm for AGNs, this trend reflects a trend of higher density at smaller radii for clouds orbiting the central collapsed object. Quantitatively this scenario may be imperfect; the observational trend typically implies $n \propto v^8$, while Keplerian motion around a central ionizing source implies $v \propto r^{-0.5}$ so that $n \propto r^{-4}$. If the ionisation is dominated by a central source, we would then expect $U \propto r^{+2}$ – which is contrary to the usual expectation that nebular ionisation is dropping with increasing radius (supported observationally by variability studies of Seyfert 1 nuclei). This apparent defect may have a simple explanation if stars are important for defining the nuclear potential so as to make the gradient in orbital velocity shallower (Filippenko & Sargent 1988). A simple mapping between density and velocity also neglects a possible weighting by ionization state and emissivity as a function of radius. Alternatively, understanding of the empirical trend might benefit from consideration of more general scenarios in which cloud compression is accompanied by acceleration.

I thank the conference organizers for partial financial support allowing me to attend this very stimulating meeting, and A. Filippenko and R. Terlevich for informative comments. My work on AGNs is supported by NASA through grant #HF-1052.01-93A from STScI, which is operated by AURA under NASA contract NAS5-26555.

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