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The Nature of the Energy Source in LINERs

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Abstract. LINERs are found in ~30% of all bright galaxies, including luminous infrared galaxies. They form a heterogeneous class powered by a variety of ionizing mechanisms such as low-luminosity AGNs, starbursts, shocks, or any combination of these.

In early-type spirals, LINERs are powered by a low-luminosity AGN, or by an AGN surrounded by circumnuclear star-forming regions. In luminous infrared galaxies, LINERs are powered by starbursts with associated wind-related extended shocks, and an AGN may play a minor role, if any. LINERs in some FR I radio galaxies show a strong evidence for the presence of a massive central black hole, and there are indications for the existence of shocks in the nuclear disks of these galaxies. Yet, the dominant ionizing mechanism for LINERs in radio-quiet ellipticals and FR I host galaxies is still unclear.

Multifrequency high spatial resolution imaging and spectroscopy are essential to discriminate among the different ionizing mechanisms present in LINERs.

1. Introduction

Low-ionization nuclear emission-line regions (LINERs) were first defined as a class using the optical oxygen emission-line ratios (Heckman 1980). Following Heckman, a galaxy is classified as a classical LINER if [O II] λ3727/[O III] λ5007 ≥ 1 and [O I] λ6300/[O III] λ5007 $\geq 1/3$. Other criteria designed to minimize extinction effects in the line ratios (Veilleux & Osterbrock 1987; Ho, Filippenko, & Sargent 1993) classify galaxies with [N II] λ6583/H$\alpha \geq 0.6$, [S II]$\lambda\lambda$6717,6731/Hα ≥ 0.4 also as LINERs. LINERs are further classified as weak-[O I] LINERs if the [O I]/Hα ratio is smaller than 1/6.

Heckman (1980) proposed that LINERs were produced by shocks in a low-density medium. However, several other ionizing mechanisms such as low-luminosity AGNs (Ferland & Netzer 1983), hot high-metallicity O-type stars (Filippenko & Terlevich 1992; Shields 1992), radiative shocks in accretion flows or winds (Dopita & Sutherland 1995), or UV-bright post-AGB stars (Binette et al. 1994) have been invoked as the energy sources of LINERs.

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What is the nature of the energy source powering LINERs? Are LINERs the low-luminosity end of AGNs? These are some of the fundamental questions still unanswered. To properly address these questions, the various proposed energy sources have to be distinguished observationally, and their energy contribution quantified. Studies involving only optical emission-line ratios are not capable of differentiating among the several proposed ionizing mechanisms. Multifrequency observations to search for additional signatures of AGNs (i.e., a bright UV & X-ray nuclear point-like source with a featureless continuum), of young hot stars (i.e., UV absorption lines), and of winds and shocks (i.e., strong UV emission lines; velocity splitting in the line profiles) are needed.

This paper summarizes the empirical evidence for the presence of various ionizing mechanisms in LINERs. There is some evidence that the nature of the energy source depends on the properties of the host galaxy. Most of the results shown here are based on recent high spatial-resolution ultraviolet and optical observations of LINERs obtained with the *Hubble Space Telescope (HST)*. Recent reviews by Filippenko (1993) and Reichert (1993) concentrate on pre-*HST* optical and ultraviolet properties of LINERs, respectively. A detailed account of the various proposed ionizing mechanisms, and of the observations covering the entire wavelength range, can be found in the proceedings of the conference *The Physics of LINERs in View of Recent Observations* (1996, ed. Eracleous et al.).

2. Demographics of LINERs

The original survey of bright galaxies by Heckman (1980) and several other surveys (see Ho 1996 for a review) have established that LINERs are a common phenomenon in all types of bright galaxies, except late-type spirals and irregulars.

The Palomar survey of nearby galaxies, a magnitude-limited survey of about 500 galaxies (Ho 1996), has confirmed and quantified these previous findings. LINERs are found in about a third of all bright galaxies, with as much as 40% of E–E/S0 and 60% of Sa–Sab galaxies showing LINER optical spectra (see Table 1 and Ho 1996). In contrast, LINERs represent only about 14% of late-type spirals and irregulars.

LINERs are also common in luminous infrared galaxies (LIRGs). A recent survey found LINERs in about 30% of 200 LIRGs selected from the *IRAS* Bright and *IRAS* Warm Galaxy Surveys (Veilleux et al. 1995). The fraction of LINERs in luminous infrared galaxies was also found to be independent of the absolute infrared luminosity (Veilleux et al. 1995).

3. LINERs in Early-Type Spirals

3.1. UV-Bright Versus UV-Dark LINERs

The search for the existence of an ultraviolet-bright point-like central source in the nucleus of LINERs has recently been undertaken by Maoz et al. (1995) and Barth et al. (1996) using the *HST* FOC and WFPC2 cameras, respectively. Only 22% of the surveyed LINERs show a compact UV-bright nucleus (UV-bright

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Table 1. Percentages of Active Galaxies in Low-Redshift Galaxy Surveys

Type	E–E/S0	S0–S0/a	Sa–Sab	Sb–Sbc	Sc–Irr	LIRG
LINER	41	40	60	37	14	27
Seyfert	12	16	15	17	8	14
H II	0	12	24	45	77	59

LINER). Of these, 63% have an inclination of less than 45°, while no LINERs with an inclination larger than 65° show a UV-bright nucleus. Moreover, none of the LINERs with nuclear dust lanes have been detected in the ultraviolet. These results indicate that internal extinction plays a crucial role in detecting UV-bright LINERs. Also, the fact that UV-bright and UV-dark LINERs show no difference in the emission-line ratios and span the same range in Hα luminosities, supports the conclusion that many more UV-dark LINERs have a UV ionizing source in their nuclei. Therefore, the fraction of detected UV-bright nuclei has to be considered as a lower limit of the total fraction of LINERs with central ultraviolet compact sources.

However, the nature of this ultraviolet source is not yet clear. The size of the source ($\sim$ several parsecs) and its UV luminosity ($\log L(2100\,\text{Å}) \approx$ 40–41 ergs s^{-1}) is consistent with either the existence of a low-luminosity AGN, or a cluster of young hot stars. Moreover, the detection of several surrounding point sources, diffuse emission, and/or faint extended emission in many of the UV-bright LINERs (Maoz et al. 1995) argues against the existence of an isolated compact ionizing source centered on the nucleus. Additional UV spectroscopy, to search for a featureless continuum and/or broad UV stellar absorption lines, is needed to differentiate the AGN from a cluster of young hot stars.

3.2. Classical LINERs: NGC 3031 and NGC 3642

Classical LINERs in early-type spirals are the most likely candidates for low-luminosity AGNs. NGC 3031 (M 81) presents the best example of this class. Recent *HST* FOS ultraviolet (Ho, Filippenko & Sargent 1996) and optical (Bower et al. 1996) spectra of the nucleus of M 81 shows the presence of broad emission lines, some of them (Hβ and Hα) variable with a transitory double-peaked broad profile ($FWZI \approx 12{,}500\,\mathrm{km\,s^{-1}}$; Bower et al. 1996). The broad-line region is characterized by an ionization parameter $U \leq 10^{-2.8}$, and electron density $N_e \approx 10^9$–$10^{10}\,\mathrm{cm^{-3}}$, i.e., physical parameters typical of Seyfert 1 galaxies. However, the featureless ultraviolet continuum has a steep spectral index ($\alpha = -2.0 \pm 0.3$ rather than -0.5 to -1) and does not show the 'big blue bump' detected in Seyfert 1 galaxies (Ho et al. 1996). It is not yet clear if these spectral characteristics indicate low accretion rates.

The radio and X-ray fluxes also favor the presence of an AGN in M 81. VLBI monitoring over a decade (Bietenholz et al. 1996) shows the presence of a point-like (0.18×0.07 mas) nuclear radio source with no indications of either flux variability or expansion velocity. The existence of a bright young radio supernova is ruled out as a power-law temporal decay in flux and expansion velocities of at least several hundred $\mathrm{km\,s^{-1}}$ would be expected. Finally, the M 81 nuclear $L_X/L(\mathrm{H}\alpha)$ and $L_X/L_{5\,\mathrm{GHz}}$ ratios are similar to those of Seyfert galaxies (Pérez-Olea & Colina 1996).

NGC 3642 is also a classical LINER where evidence for the presence of a low-luminosity AGN has been accumulating. The nucleus of NGC 3642 is detected as an unresolved (size ≤ 10 pc) UV source (Barth et al. 1996) and also as an X-ray source (Koratkar et al. 1995). There is evidence of a faint broad Hα emission line ($FWZI \approx 3000\,\mathrm{km\,s^{-1}}$; Koratkar et al. 1995). Moreover, the nuclear $L_X/L(\mathrm{H}\alpha)$ ratio agrees with the value measured in Seyferts (Koratkar et al. 1995) and is two orders of magnitude larger than that of starbursts (Pérez-Olea & Colina 1996).

3.3. Weak–[O I] LINERs: NGC 1097 & NGC 3504

About 50% of the LINERs detected in early-type spirals (Sa–Sbc) show a weak [O I] λ6300 emission line, i.e., [O I]/H$\alpha < 1/6$ (Ho 1996). These weak-[O I] LINERs are believed to be galaxies where a low-luminosity AGN coexists with nuclear or circumnuclear star-forming regions (Ho et al. 1993).

NGC 1097 has a classical LINER nucleus (Phillips et al. 1984) surrounded by a circumnuclear ring of luminous star-forming regions (Hummel, van der Hulst, & Keel 1987). The ring dominates the Hα luminosity, but contributes only to $\sim 20\%$ of the total soft X-ray luminosity. The nuclear luminosity of $\log L_X = 41.3\,\mathrm{ergs\,s^{-1}}$, nuclear $L_X/L(\mathrm{H}\alpha)$ and $L_X/L_{5\,\mathrm{GHz}}$ ratios that are similar to those of Seyfert 1 galaxies (Pérez-Olea & Colina 1996), and recent optical observations of a broad ($FWZI \approx 21{,}000\,\mathrm{km\,s^{-1}}$) variable H$\alpha$ emission line (Storchi-Bergmann et al. 1995) all provide evidence for a Seyfert-type nucleus. Thus, NGC 1097 could be reclassified as a low-luminosity Seyfert 1 nucleus surrounded by a star-forming ring.

NGC 3504 also shows a bright nucleus surrounded by a star-forming ring at a projected radius of $\sim 2''$. The Hα luminosity is dominated by the star-forming ring with $L_{ring}(\mathrm{H}\alpha) \approx 6L_{nucleus}(\mathrm{H}\alpha)$. Recent long-slit optical spectroscopy (Colina et al. in prep.) shows that the nucleus ($\leq 1''$) can be classified as a weak-[O I] LINER while the integrated spectrum (nucleus plus star-forming ring) shows spectral characteristics close to those of H II regions.

4. LINERs in Ellipticals

4.1. Radio-Quiet Ellipticals Versus FR I Galaxies

LINERs in radio-quiet ellipticals ($\log L^{core}_{5\,\mathrm{GHz}} \approx 20.5\,\mathrm{W\,Hz^{-1}}$) and in low-luminosity radio ellipticals (FR I; $\log L^{core}_{5\,\mathrm{GHz}} \approx 23.0\,\mathrm{W\,Hz^{-1}}$) are indistinguishable in their optical emission-line properties. The warm ionized gas shows a circumnuclear distribution peaked at the nucleus of the galaxy, with characteristic sizes of a few kpc and Hα luminosities of 10^{39}–$10^{40}\,\mathrm{ergs\,s^{-1}}$ (Phillips et al. 1986; Goudfrooij et al. 1994; Macchetto et al. 1996; Colina, unpublished). The emission-line luminosity of radio-quiet ellipticals and of FR I galaxies of the same optical magnitude is similar, but if the optical-magnitude to line-luminosity correlation is removed, there is only a weak residual correlation of line and radio luminosity in FR I galaxies (Baum, Zirbel, & O'Dea 1995). These results suggest that the ionizing source in radio-quiet and FR I ellipticals is the same and is associated with the host galaxy itself.

Models considering the presence of old UV-bright post-AGB stars are able to explain the observed LINER optical spectrum and the Hα luminosity in bright ellipticals (Binette et al. 1994). However, post-AGB stars contribute no more than $\sim$ 40% of the flux in the 912–1800 Å band spectrum of ellipticals (H. Ferguson, private comm.), thus additional ionizing sources need to be invoked to explain the UV spectrum. The nature of the ionizing source in radio-quiet and FR I ellipticals is still not clear. Searches for unresolved UV bright nuclei in ellipticals with *HST* would help to differentiate a point-like AGN from a less compact stellar or shock component.

4.2. Weighing Massive Black Holes: NGC 4261 and NGC 4486

The radio ellipticals NGC 4261 and NGC 4486 are, together with NGC 4258, the best examples of active galaxies supporting the AGN paradigm.

The nucleus of NGC 4261 (central 14.5 pc) shows LINER-like emission-line ratios and a broad ($FWZI \approx 6000\,\mathrm{km\,s^{-1}}$) H$\alpha$ emission line (Ferrarese, Ford, & Jaffe 1996). The nuclear gas and dust disk, is characterized by a size of 240 pc, a mass of $10^5 M_\odot$, and with the minor axis almost aligned with the direction of the double-sided radio-jet source 3C 270 (Jaffe et al. 1993, 1996). *HST* high spatial-resolution FOS spectroscopy of the nuclear disk have been used to map the velocity field around the nucleus, and to measure the mass concentration inside 0″.1 (Ferrarese et al. 1996). These authors conclude that a mass of $4.9\,(\pm 1.0) \times 10^8 M_\odot$ with a mass-to-light ratio of $(M/L)_V \approx 2130 M_\odot/L_\odot$ is concentrated within the inner 14.5 pc.

NGC 4486 (M 87) is the dominant elliptical galaxy of the Virgo cluster and hosts the well-known radio-jet source 3C 274 detected at radio, optical, and ultraviolet wavelengths (Sparks, Biretta, & Macchetto 1996). The nucleus of M 87 (central 18 pc) has a classical LINER optical spectrum and shows a broad ($FWZI \approx 4300\,\mathrm{km\,s^{-1}}$) H$\alpha$ emission line (Harms et al. 1994). M 87 has a nuclear spiral disk of ionized gas (size $\sim$ 146 pc) oriented approximately perpendicular to the radio jet (Ford et al. 1994). A mass concentration of $2.4\,(\pm 0.7) \times 10^9 M_\odot$ with a mass-to-light ratio $(M/L)_I = 170 M_\odot/L_\odot$ has been measured within the inner 18 pc (Ford et al. 1994; Harms et al. 1994).

The high spatial-resolution, long-slit capabilities of *HST* STIS will allow measurements of the mass concentration in the nucleus of many more low-redshift FR I galaxies and radio-quiet ellipticals with known nuclear disks of ionized gas and dust (de Juan, Colina, & Golombek 1996; Macchetto et al. 1996). Thus, the presence of central massive black holes in ellipticals, and their mass distribution as a function of the host-galaxy properties can be established.

4.3. Shocks in a Nuclear Disk: NGC 4486

Indications for the presence of ionization associated with shocks in the nuclear disk of M 87 have recently been obtained by Dopita and coworkers. A complete 1200–6800 Å spectrum of an off-nuclear region along the major axis of the M 87 nuclear disk has been obtained for the first time with the *HST* FOS spectrograph (Dopita et al. 1996). The spectrum shows strong ultraviolet emission lines compatible with ionization by high velocity ($\sim 200\,\mathrm{km\,s^{-1}}$) shocks, and inconsistent with photoionization by a low-luminosity, low-ionization parameter AGN (Dopita et al. 1996). These new observations indicate that the ionizing source in, at least, some FR I host galaxies could be a combination of a low-luminosity AGN and shocks. These shocks are produced in the inner regions of nuclear disks as the gas spirals down and looses angular momentum. Future UV–optical long-slit observations with *HST* STIS spectrograph will allow investigations of these issues in M 87 and many other radio galaxies. These will help to establish the contribution of shocks to the ionization in the nuclear regions of FR I host galaxies.

5. LINERs in Luminous Infrared Galaxies

There are several empirical arguments favoring starbursts and extended shocks as the ionizing source of LINERs in LIRGs. About 75% of the LINERs detected in LIRGs have [O I]6300/Hα $\leq$ 0.1, i.e., belong to the weak-[O I] class. As shown before (§3.3), this indicates that the nuclear/circumnuclear star-forming regions contribute substantially to, or even dominate, the Hα luminosity. Other lines of evidence that indicate that starbursts may be the dominant source of activity in LIRGs are: (1) $L_X/L(\mathrm{H}\alpha)$ and $L_X/L_{5\,\mathrm{GHz}}$ ratios observed in the luminous infrared galaxy Arp 220 are similar to those measured in nearby almost edge-on starbursts, and two magnitudes lower than those measured in classical LINERs like M 81 or NGC 3642 (Pérez-Olea & Colina 1996); (2) the far-infrared to radio-flux relation observed in LIRGs follows closely the extrapolation of the relation found in spirals, and can be explained by invoking starbursts with radio supernovae (Colina & Pérez-Olea 1995); (3) The average Hα luminosities measured in LIRGs ($\log L(\mathrm{H}\alpha) = 42.0\,\mathrm{ergs\ s^{-1}}$; Veilleux et al. 1995) are much larger than in classical LINERs (for example, $\log L(\mathrm{H}\alpha) \approx 39\,\mathrm{ergs\ s^{-1}}$ in M 81 and NGC 3642).

The existence of strong high-velocity shocks is likely to occur in the winds and bubbles produced by the starbursts in LIRGs. Extended double-peaked narrow optical emission lines with a velocity splitting of 200–$600\,\mathrm{km\,s^{-1}}$, and up to $2000\,\mathrm{km\,s^{-1}}$ in NGC 3079 (Veilleux et al. 1994) have been observed, and are interpreted as evidence for the presence of starburst related superwinds in LIRGs (Heckman et al. 1990).

6. Summary

LINERs are found in about 30% of all bright galaxies, including luminous infrared galaxies. In ellipticals and early-type spirals, this fraction increases up to 40% and 60%, respectively.

LINERs form an heterogeneous class of galaxies powered by a variety of physical mechanisms including low luminosity AGNs, nuclear/circumnuclear starbursts, shocks, or any combination of these mechanisms (see Table 2 for a summary).

Classical LINERs in early-type spirals show the multifrequency characteristics of low-luminosity AGNs. Weak-[O I] LINERs show evidence of an AGN surrounded by nuclear/circumnuclear star-forming regions, where the stellar component contributes substantially to, or even dominates, the ionizing flux.

LINERs in FR I radio host galaxies like NGC 4261 and M 87 show strong evidence for the existence of a central supermassive black hole, and therefore of the AGN paradigm. LINERs in radio-quiet ellipticals and FR I radio galaxies are indistinguishable in their optical emission-line properties. The dominant ionizing source is still unclear and could be associated with the stellar component of the host galaxy.

LINERs in luminous infrared galaxies are powered by starbursts and extended shocks. The AGN may play a minor role, if any.

High spatial-resolution ($\sim 0''.1$), multifrequency observations of prototypical LINERs are needed to identify the nature of the different ionizing mechanisms operating in LINERs, and quantify their relative contribution to the energy output.

Table 2. LINERs versus Ionization Mechanisms

Galaxy	Type	AGN	Starburst	Shocks	Stars
E/S0	Classical	Y?	N	Y?	Y
Sa/Sc	Classical	Y	N?	N?	N
Sa/Sc	[OI]-weak	Y	Y	N	N
FR I	Classical	Y	N	Y	Y?
LIRG	[OI]-weak	N	Y	Y	N

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