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Ionized Gaseous Nebulae (Mexico City, 21-24 November 2000)
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# PHOTOIONIZATION, SHOCKS OR STARBURSTS?

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## RESUMEN

Desde que Baldwin, Phillips, y Terlevich; así como Osterbrock y Veilleux popularizaron su uso, los diagnósticos ópticos han sido utilizados para tratar de distinguir entre los varios modos de excitación en regiones nucleares de emisión en galaxias normales y activas. Recientemente se ha hecho gran progreso reuniendo nuevos datos observacionales y construyendo modelos teóricos para describir los resultados. Revisaremos estos resultados, intentaremos mostrar cuáles parámetros de las regiones de emisión nuclear pueden ser derivados unívocamente a partir de diagnósticos ópticos y UV, y señalaremos el camino hacia nuevos progresos en este problema

## ABSTRACT

Since Baldwin, Phillips, & Terlevich and Osterbrock & Veilleux popularized their use, optical diagnostic plots have been used to attempt to distinguish between the various modes of excitation in nuclear emission regions of both active and normal galaxies. Recently, great progress has been made in gathering new observational data, and in building theoretical models to describe the results. We will review these results, and attempt to show what parameters of the nuclear emission regions can be unequivocally derived from optical and UV diagnostics, and point the way towards making further progress in this problem.

*Key Words:* **HYDRODYNAMICS — GALAXIES: SEYFERT — GALAXIES: ACTIVE — ISM: JETS AND OUTFLOWS**

## 1. INTRODUCTION: THE NUCLEAR ZOO

Optical spectroscopy of the narrow emission line gas around galactic nuclei reveals that it is subject to a large variety of excitation mechanisms. The optical diagnostic diagrams of Baldwin, Phillips, & Terlevich (1981), Veilleux & Osterbrock (1987) and Osterbrock et al. (1992) have enabled us to identify three major modes of excitation of the ionized gas: nuclei excited by star formation (giving H II region-like spectra), and the two classes of emission regions known to by excited by a bone-fide active galactic nucleus (AGN); Seyfert narrow line regions (NLRs) and Low Excitation Nuclear Emission Line Regions (LINERs).

We now have available extensive homogeneous sets of high-quality spectrophotometric data covering large samples of galactic nuclei. Amongst the most important of these we should mention the complete sample of southern elliptical galaxies by Phillips et al. (1986), the similar-sized sample of nearby northern spirals by Ho, Filippenko & Sargent (1995), the compilations of Veilleux & Osterbrock (1987), and Véron-Cetty & Véron (2000), the Seyfert galaxy study of Veilleux (1991a,b,c), the compact radio-luminous sample of Gelderman & Whittle (1994), the luminous infrared galaxy survey of Kim et al. (1995), the ultraluminous infrared galaxy survey of Kim et al. (1998) and Veilleux, Kim, & Sanders (1999), and finally, the warm IRAS sample of Kewley et al. (2001a).

The Seyfert galaxies are generally found in spiral galaxy hosts, often show lines of high-excitation, frequent evidence of non-gravitational motions, and are radio-quiet, although weak collimated radio-jets are frequently seen in such objects. There are often close correlations seen between the radio and the optical morphology (Allen et al. 1999; Axon et al. 1998; Bower et al. 1995 ; Capetti et al. 1995; Falcke, Wilson, & Simpson 1998; Haniff, Wilson, & Ward 1988; Whittle et al. 1988). These observations confirm that the structure of the NLR in many Seyfert galaxies is dominated by compression of interstellar gas by the bubbles of partly relativistic gas ejected from the nucleus.

Both spiral and elliptical galaxies can exhibit LINER spectra. However, LINERs are more frequently found in Ellipticals. Elliptical LINER galaxies cover a range of radio properties, including radio quiet objects, weak nuclear sources, and Fanaroff-Riley (FR) Class I sources. LINERs are never found in the high-power FR II radio sources. In terms of the correlation between the optical and the radio luminosities, a similar trend emerges Baum, Zirbel, & O'Dea 1995. There is a good correlation for the FR II class, but this disappears smoothly at the FR I–II transition. Ho et al. (1995) have shown that some low level LINER activity is even more ubiquitous than had been suspected in both elliptical and spiral galactic nuclei.

The high-power compact radio sources in elliptical galaxies are generally found to be associated with emission spectra similar to Seyfert galaxies. Such sources include the steep-spectrum radio sources (CSS) (Fanti et al. 1990), the Gigahertz-peaked sources (GPS) (O'Dea et al. 1990, and references therein), the compact symmetric objects (CSO) (Wilkinson et al. 1994, and references therein) or the compact double sources (CD) (Phillips & Mutel 1982). Together, these represent an appreciable fraction (10–30%) of the luminous radio sources. Not only are these sources very luminous at radio frequencies, but they also are very luminous in optical emission lines. The spectra of Gelderman and Whittle (1994) reveal the broad emission lines of the AGN itself as well as intense "narrow line" emission reminiscent of Seyfert 2 galaxies. These connections with radio power, and the continuity of properties across these different classes of sources argues strongly that the same physical processes are at work in all of them, and that the kinetic energy supplied by the radio-emitting jets may provide a substantial fraction of the power radiated in the NLRs of these galaxies. The power requirements for Seyfert 2 galaxies are relatively modest, typically between $10^{41}$ and $10^{44}$ ergs $s^{-1}$, while the luminous radio sources require far more energy; $10^{45}$–$10^{46}$ erg $s^{-1}$.

Finally, the galaxies associated with intense circumnuclear star formation are frequently those which emit the bulk of their radiation in the infrared. The Infrared Astronomical Satellite (IRAS) revealed a large population of these galaxies, many of which have $\log(L_{\rm FIR}) > 11.0$ and are referred to as luminous infrared galaxies (LIRGs). Although it is clear that the IR luminosity derives from dust reprocessing of other sources of luminosity in the galaxy, the nature of the nuclear source is still a current issue of debate. Most ultraluminous samples (e.g., Goldader et al. 1995) and the majority of lower luminosity IRAS galaxies Kim et al. (1995) are star formation dominated. Indeed, Condon, Anderson ,& Helou (1991) have concluded that the far infrared luminosity and radio properties of LIRGs can be explained by compact nuclear starburst events. However, Sanders et al. 1988 have argued that LIRGs contain a dust enshrouded AGN and Veilleux, Sanders & Kim (1997) have used near IR and optical spectroscopy to search for broad emission lines, indicative of AGN, which they found in some 25–30% of ULIGs of their sample. Confusing the question of the powering mechanism still further, some studies of LIRGs have concluded that Active Galactic Nuclei (AGN) to be the dominant powering mechanism (e.g., Lonsdale, Smith & Lonsdale 1993), while in some cases, such as Arp 220 (Smith, Lonsdale, & Lonsdale 1998), both mechanisms contribute to the overall energy output.

In this review, we will examine how theoretical modeling combined with line ratio diagnostics are gradually enabling us to understand this rich phenomenology, allowing us to gain insight into the physical and chemical conditions and the mode of excitation of this circumnuclear ionized gas.

## 2. MODELING

Currently, three types of model are available for the interpretation of line-ratio diagnostics. First, photoionization by photons originating at or near a compact nuclear source (see, e.g., Koski 1978; Ferland & Osterbrock 1986; Osterbrock 1989). Here, the EUV spectrum is generally assumed a smooth featureless power-law, or a broken power-law. A variation on such models is to assume that the power-law EUV spectrum passes through a highly-ionized screen of diffuse gas, before being absorbed in the vicinity of dense clouds Binette, Wilson, & Storchi-Bergmann (1996). Although such models produce generally good results when compared with observations, a major problem with this class of models is that the geometry of the ionized gas is arbitrary, and a free parameter.

The second class of models designed to produce Seyfert or LINER spectra is by means of photoionizing fast radiative shocks (Dopita & Sutherland 1995,1996). Apart from their shock velocity, $v_{\rm s}$ , such shocks are characterized by their Alfvén Mach Number, $\mathcal{M}_{\rm A} = v_{\rm s}/v_{\rm A}$ where $v_{\rm A}$ is the Alfvén velocity in the transverse component of the pre-shock magnetic field, $v_{\rm A}^2 = B^2/4\pi\rho_0$. The Alfvén Mach Number controls the emergent spectrum by moderating the compression in the post-shock plasma:

$$\frac{\rho_1}{\rho_0} = 2^{1/2}\mathcal{M}_{\rm A}.$$

Dopita & Sutherland distinguish two limiting cases; *shock only* in which the precursor gas is optically thin to the upstream EUV photons, and *shock plus precursor*, in which there is enough gas around to completely absorb these upstream photons. The first case is encountered in gas-poor environments,

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such as in the shocked disk of M87 Dopita et al. (1997), while the second case characterizes regions with a dense and extensive ISM surrounding the shocked region.

A major problem with these shock models, as pointed out in the original papers, but generally ignored by observers, is that fast shocks are thermally unstable, as first considered by Innes, Giddings & Falle (1987a). New multi-dimensional hydrodynamical shock models by Sutherland (2002, in prep.) should rectify this situation, and produce more realistic spectral predictions for fast shocks.

Finally, for regions excited by circumnuclear starburst there are photoionization models in which the input spectrum is taken to be that of a cluster of hot OB stars, which may be either young and unevolved (Dopita et al. 2000) or else older, and in a state of dynamic equilibrium between star births and star deaths (Kewley et al. 2001b). For the latter case, the emergent spectrum depends critically upon the ionizing spectrum produced by the Wolf-Rayet stars. Kewley et al. (2001a) find that this introduces a major uncertainty in EUV spectra predicted by the stellar population synthesis models PEGASE (Fioc & Rocca-Volmerange 1997) or STARBURST99 (Leitherer et al. 1999). The PEGASE code utilizes the Padova group's tracks while STARBURST99 uses the Geneva tracks. The ionizing stellar continuum predicted by PEGASE is harder in the 1-4 Ryd range than that of STARBURST99. However, neither can properly reproduce the H II region sequence observed by Kewley et al. (2001b). The problem appears to be that only the STARBURST99 code uses extended-atmosphere models by Schmutz et al. (1992) for the Wolf-Rayet star atmospheres, and these contain only hydrogen and helium as sources of opacity. The accuracy of the modeling of old clusters cannot be improved until models with heavy-element bound-free continuum opacities become available.

## 3. LINE RATIO DIAGNOSTICS

### 3.1. *H II Regions*

Assuming that the metallicity and the shape of the EUV spectrum are defined, the local ionization state in an H II region is characterized by the ionization parameter $U \equiv q/c = S_{\rm H}/cn$, where $S_{\rm H}$ is the ionizing photon flux through a unit area, and $n$ is the local number density of hydrogen atoms. $q$ can be physically interpreted as the maximum velocity of an ionization front that can be driven by the local radiation field. On the Veilleux & Osterbrock (1987) diagnostic diagrams, the H II region models are constrained to lie in a region below, and to the left of, a critical line. The position of this line is most sensitive to the exact shape of the EUV spectrum which is exciting the H II region. This line corresponds to a "fold" in the ionization-parameter–metallicity two-parameter surface. As a consequence, a wide range of both ionization parameters and metallicities map onto a fairly narrow strip of line ratio space. It is for this reason that there is such a well-defined sequence for extragalactic H II regions.

For the extragalactic (non-nuclear) H II regions Dopita et al. (2000) found that the observed sequence is reproduced remarkably well by their models, provided that the clusters which excite them are all rather young (< 2 Myr). This is most likely an observational selection effect. To obtain the ionization parameter, the line ratio that is usually used for this purpose, [O III] 5007 Å/[O II] 3726, 9 Å, is excellent, although somewhat dependent on the metallicity. The [O III] 5007 Å/[N II] 6583 Å line ratio can also be used for the same purpose. It too has an abundance sensitive behavior, but for both, the ambiguities can be raised by plotting these ratios against a good abundance-sensitive ratio. Amongst other easily observed line ratios we found that the [N II] 6548, 84 Å/[O II] 3726, 9 Å ratio gives the best diagnostic, as it is monotonic in abundance between 0.1 and over 3.0 times solar metallicity. Kewley & Dopita (2002) have examined other abundance diagnostic line ratios critically. They find that the $R_{23} = ([\rm O\,II] + [\rm O\,III])/\rm H\beta$ ratio is only useful at low abundance, that the $([\rm S\,II] + [\rm S\,III])/\rm H\beta$ ratio is useful over a somewhat larger range, and that, if only red spectra are available, the [N II]/[S II] ratio can be used as an abundance diagnostic above about 0.3 times solar.

### 3.2. *Starburst Galaxies*

As explained above, both nuclear and non-nuclear H II regions fall into a narrow strip on the Veilleux & Osterbrock (1987) diagnostic diagrams; although the sequences for the two are slightly different because of the greater range of stellar ages present in the circumnuclear starbursts. As Kewley et al. (2001b) have shown, for continuous star formation, the theoretical upper limit that can be achieved by H II region models on the Veilleux & Osterbrock (1987) diagnostic diagrams (in which the [N II] and [N II] line strengths are taken to be the sum of the two doublet components) can be parametrized by the following simple fitting formulae (which have the shape of rectangular hyperbolae);

$$\log\left([\rm O\,III]/\rm H\beta\right) = \frac{0.61}{\log([\rm N\,II]/\rm H\alpha) - 0.47} + 1.19, \quad (1)$$

$$\log\left([\mathrm{O\,III}]/\mathrm{H}\beta\right) = \frac{0.72}{\log([\mathrm{S\,II}]/\mathrm{H}\alpha) - 0.32} + 1.30, \quad (2)$$

$$\log\left([\mathrm{O\,III}]/\mathrm{H}\beta\right) = \frac{0.73}{\log([\mathrm{O\,I}]/\mathrm{H}\alpha) + 0.59} + 1.33. \quad (3)$$

The theoretical boundaries for starbursts defined by equations (1)–(3) provide us for the first time with a theoretical means of separating starburst galaxies from active galaxies of various types. The utility of these boundary lines can be readily checked by referring to the extensive homogeneous observations of Véron-Cetty & Véron (2000).

### 3.3. *Seyfert and other Narrow-Line Galaxies*

On the optical diagnostic diagrams of Veilleux & Osterbrock (1987) the fact that both the shock models and the photoionization models can provide a description of the observations for Seyferts or other types of narrow-line AGN merely reflects the fact that both shock models with velocities between 300 and 500 km $\mathrm{s}^{-1}$ and photoionization models with photon spectral indices of between $-1$ and $-2$ have about the right "hardness" of the photoionizing spectrum. These diagrams do not therefore effectively distinguish between the two excitation mechanisms. A curious feature of the observations, which has not yet had an adequate theoretical explanation is the tight grouping of the observational points for the Seyfert 2 galaxies. Nearly all Seyfert galaxies are located in a region with less than 0.8 dex variation in [O III] $\lambda$5007 Å/H$\beta$, [N II] $\lambda$6583 Å/H$\alpha$ or [O I] $\lambda$6300 Å/H$\alpha$ ratio Véron-Cetty & Véron 2000. Within individual galaxies, spatial variations in these line ratios are even tighter (Allen et al. 1999). While this tight grouping is a natural consequence of shock models, it is harder to understand in terms of standard photoionization modeling. In principle, the ionization parameter characterizing the NLR clouds could vary widely between different parts of of the same object, or between different objects. In practice the observations constrain the dimensionless ionization parameter to lie in the range $-3 < \log U < -2$. This (unnaturally restrictive) range suggests that, if these regions are photoionized, then some other self-regulatory process such as pressure balance between different phases is at work to ensure that the density of the photoionized clouds falls of roughly as the inverse square of the distance from the central engine.

In general, objects with a LINER-like spectra should be easier to classify, since in the optical, their spectra are either fit with a photoionization model of low ionization parameter ( $\log U \sim -4$ ), or by high velocity shocks without precursors. In the UV the spectra resulting from these two kinds of excitation are quite different; photoionized regions have low electron temperatures, and the UV spectra are weak, and of low excitation, while shock-excited regions show a rich collisionally-excited UV spectrum, lines of high ionization potential, and temperature-sensitive diagnostics give high values of electron temperature; exactly what Dopita et al. (1997) found in the case of *HST* FOS spectra of M87. Other LINERs such as M81, for example do not give such unambiguous results, because the LINER spectrum arises in a high-density circumnuclear medium with strong radial density gradients, and in this case both multi-component shock models, or photoionization models can give a fair description of the spectrum.

### 3.4. *Composite Objects*

Objects with composite spectra are particularly common in luminous IR galaxy samples. They have been identified by Kim et al. (1995), Kim et al. (1998) and Veilleux et al. (1999), the studies of Véron, Gonçalves, & Véron-Cetty (1997), Gonçalves, Véron-Cetty, & Véron (1999) and in the extensive survey of warm IR galaxies by Kewley et al. (2001b). On the optical diagnostic diagrams of Veilleux & Osterbrock (1987), such galaxies tend to lie in a broad, almost vertical band above the metal-rich starbursts, and below the region occupied by the Seyferts 2 galaxies. Such galaxies were a source of deep fascination to our beloved colleague, Charlene Heisler, who passed away on October 28, 1999. Shortly before her death, she was delighted to find the explanation for this class of objects. This is published in Kewley et al. (2001b). They find that these galaxies are excited by a combination of hot stars plus either ionization by a power-law radiation field associated with an AGN or else by shock excitation in which the shock results from such processes as cooling flows, jets, or superwind activity around an AGN/Starburst.

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