ACTIVITY IN THE NUCLEI OF NORMAL GALAXIES

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1. INTRODUCTION

The principal motivation behind the work summarized below was to define the nature of a "typical" galactic nucleus and thereby determine whether such nuclei differ from active nuclei in a qualitative or only quantitative sense. I hoped that such a study would then yield clues as to the origin and duration of nuclear activity and the effects such activity might have on the structure and evolution of the surrounding galaxy. For a more complete discussion of the results below, see my Ph. D. dissertation (Heckman, 1978) or the series of three papers (Heckman, 1979) to be published elsewhere.

2. SAMPLE SELECTION AND OBSERVATIONS

The statistically complete sample consisted of the nuclei of all galaxies in the Second Reference Catalog of Bright Galaxies (de Vaucouleurs et al., 1976) having $m_B \leq 12.0$ and $\delta \geq +40^o$. In addition, several other nuclei known to be unusually active (Disney and Cromwell, 1971) were included for comparison purposes.

The optical observations were conducted using the Image Dissector Scanner mounted on the 2.1 m telescope at the Kitt Peak National Observatory. For most of the nuclei studied only a blue spectrum (λ3500-λ5300 Å) was obtained, but for those showing relatively strong emission lines, a spectrum in the red (λ5100-λ6900) was also obtained. The observations were made through a 6 arcsec circular aperture during generally good observing conditions. The instrumental spectral resolution was $\sim$ 8 Å full width at half maximum with an instrumental profile that was very nearly Gaussian. The data was calibrated and analyzed in the standard way.

The radio observations were made using the Very Large Array. Each nucleus was observed at 4885 and 1480 MHz for a total of $\sim$ 40 minutes at four different hour angles. The resulting beam had a full width at

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half intensity of 1.7 and 4 arcsec at the two respective frequencies. Because of the lack of short spacings these observations were of quantitative value only for detection of barely resolved or unresolved radio components.

3. RESULTS

The major result of this investigation was the discovery of a class of optical emission line region found in the nuclei of normal galaxies of which few previous examples had been known. I have called these objects LINER's for Low Ionization Nuclear Emission-Line Regions, and the principal characteristics of the class are as follows:

a. The low ionization lines are relatively strong (e.g. [OII] λ3727, [OI]λλ6300+6363, [NII]λλ6584+6548, [SII] λλ6717+6731 are strong relative to [NeIII]λλ3869+3968, [OIII]λλ5007+4959, HeII λ4686). The forbidden lines are moderately strong relative to the permitted recombination lines unlike the case in a low excitation H II region, and a wide range in ionization states are simultatneously seen (e.g. $O^{0} \rightarrow O^{+2}$). Table 1 illustrates the spectrum of M81 = NGC 3031 which is a typical example of the class. Fig. 1 displays the relationship of LINER's to Seyfert galaxies in terms of the relative strengths of the [OI] , [OII] , and [OIII] lines.

b. The luminosity of a LINER is generally quite modest, being more typical of a giant HII region than of a Seyfert galaxy (e.g. $L_{H\alpha} \sim 10^{39}$ erg s^{-1}.

c. LINER's were detected in ∿ 50% of the early type (Sb or earlier) galaxies in the statistically complete sample but in only ∿ 10% of later type galaxies. They are thus far more common than Seyfert galaxies and preferentially occupy a somewhat different range in Hubble type.

d. LINER's occur with a greater relative frequency in nuclei having a compact radio source (67%) than they do in the other nuclei (27%). For the set of galaxies having both a LINER and compact nuclear radio source, the LINER emission line flux correlates with the radio source flux density.

Table I
Spectrum of NGC 3031 = M 81

Line	Relative Intensity (Hβ = 100)
[OII]λ3727	260
[NeIII]λ3869	40
[SII]λ4069+4076	50
Hγ	50
Hβ	100
[OIII]λ5007	230
[OI]λ6300	320
Hα	730
[NII]λ6584	1000
[SII]λ6717	160
[SII]λ6731	240

e. The emission line widths in LINER's range from < 300 km s^{-1} to 1000 km s^{-1} full width at half maximum. This is similar to the range covered by the narrow line component in Seyfert galaxies (e.g. Koski, 1978). There is some indication that the lines are broader in the higher luminosity LINER's and in nuclei having relatively powerful compact radio sources. In the case of NGC 3998, weak broad wings are seen on the Hα line, similar to those found in type 1 Seyfert galaxies. Finally, there is tentative evidence that not all the emission lines in a given LINER have the same widths. [OI]λ6300 is often the most strikingly disparate line in this sense.

f. I find no evidence for a featureless, blue "non thermal" continuum in LINER's from a comparison of the observed continuum shape and stellar absorption line equivalent widths in LINER's to those in quiescent nuclei of galaxies having similar Hubble type. This is unlike the case in typical Seyfert and emission-line radio galaxies (Koski, 1978; de Bruyn and Sargent, 1978).

g. The most active nuclei in my sample tend to occur in conjunction with very high nuclear stellar metal abundances (as judged by the strength of the prominent stellar metallic absorption features). Furthermore, there is a lack of relatively high luminosity LINER's in optically faint nuclei.

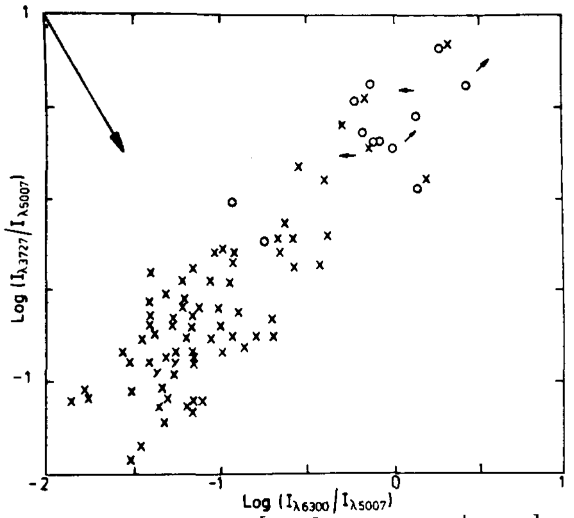

Figure 1. The [OII]λ3727 to [OIII] λ5007 vs. the [OI]λ6300 to [OIII] λ5007 log flux ratios for LINER's in our sample (open circles and arrows) and Seyfert and radio galaxies from the literature (crosses). The arrow in the upper left indicates the reddening vector corrresponding to $\tau_{H\beta} = 5$ (the plotted data is not corrected for reddening).

4. MODELS

Photoionization by a power law continuum must be considered since it is the generally accepted mechanism for the excitation of the emission lines seen in most active nuclei. Considerations of the observed Hβ luminosity and the lack of a detectable non-stellar continuum in any given LINER sets an upper limit to the spectral index (α, where $S_\nu \propto \nu^{-\alpha}$) of this continuum, provided that the continuum extends from below the Lyman edge to optical wavelengths. For the LINER's in our sample, the resulting flat spectrum ($\alpha < 1$) is incompatible with the suggestion of Costero and Osterbrock (1977) that LINER-like spectra require steep ($\alpha \gtrsim 2$) photoionizing continua. Detailed photoionization models which confirm their suggestion are needed before a full evaluation of this mechanism with regard to LINER's can be made. The possibility that LINER's are photoionized by a spectrum which cuts off before reaching optical wavelengths can not at present be excluded.

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Photoionization by hot stars, as is the case for normal H II regions and planetary nebulae is probably not a realistic possiblity for the LINER's because the characteristics of the spectra are so different (the simultaneous presence of [OII]λ3727, [OIII]λ5007, and [OI]λ6300 with comparable strength is not observed in nebulae photoionized by a "black body" type of ultraviolet continuum).

Heating and ionization of a mostly neutral gas by soft X rays or by super thermal protons has been considered by Bergeron and Souffrin (1971) and provides a relatively good match to the typical LINER spectrum. However, such models predict electron temperatures of only ∿ 5000 - 10000 K whereas at least some LINER's have temperatures of 30.000 to 40.000 K in the O^{+2} zone (eg. Fosbury et al. 1977, 1978). These high temperatures are also very difficult or impossible to explain in photoionization models discussed above.

Shock wave heating is the mechanism which seems to be most compatible with the data. The models of Dopita (1977) and Raymond (1977) are able to reproduce the observed spectra reasonably well using shock waves with a velocity of ∿ 100 km s^{-1} moving into an ambient medium with a density of ∿ 10 - 100 cm^{-3}. The great variety of adjustable model parameters seems to preclude any unique solution for the detailed shock conditions however. If indeed LINER's are excited by shock waves, the origin of those shock waves is a fundamental question which my data is however not adequate to address.

5. DISCUSSION

Although LINER's seem to be a distinct phenomenon relative to Seyfert nuclei or quasars, it may well be instead that they are joined by a continuity of properties. Figure 1 shows that the border between Seyferts and LINER's is not well defined in terms of characteristic line ratios. Moreover, although known Seyferts tend to be more luminous than LINER's this may reflect the different selection processes more than important physical distinctions. In any case, considerable overlap in luminosity does occur. The same arguments might also be applied to the greater relative prominence of a nonstellar continuum in Seyfert galaxies (since the Markarian survey selected Seyferts with prominent ultraviolet continua). Also, examples of both nuclei with LINER-type spectra and strong nonstellar continua and nuclei with Seyfert-type spectra and weak nonstellar continua are known (e.g. Koski, 1978).

Finally, as indicated in figure 2 (at least for type 2 Seyfert galaxies and LINER's considered together) there is an indication that the relative strength of the low ionization lines increases with the average electron temperature in the O^{+2} zone. One possibility for explaining figure 2 (and the general continuity between LINER's and Seyfert nuclei) is that both photoionization and shock heating contribute to the excitation of the emission line region. The former leads to highly ionized gas of low temperature and is the dominant excitation mechanism in

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Seyfert galaxies. The latter mechanism leads to gas that is hot, but not highly ionized and dominates the excitation in LINER's. Clearly, these ideas need to be explored in more detail from both a theoretical and observational standpoint.

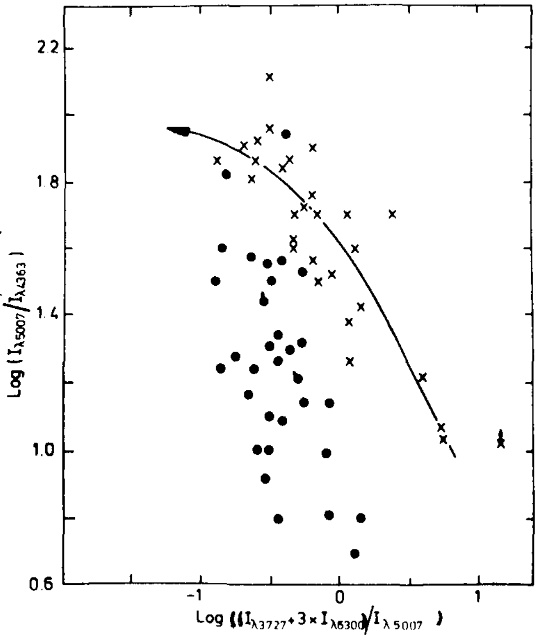

Figure 2. The [OIII]λ5007 to λ4363 vs. the [OII] λ3727 plus three times the [OI] λ6300 to [OIII] λ5007 log-flux ratios. Crosses indicate "narrow-line" active nuclei (including LINER's) while dots indicate "broad-line" active nuclei. The arrow indicates the superposition of typical LINER plus Seyfert spectra in varying relative amounts.

6. CONCLUSION

LINER's bridge the gap between active and quiescent nuclei which has long been supposed to exist. This type of activity, which occurs quite commonly in typical galactic nuclei, probably differs from that occuring in Seyfert galaxies and quasars in both a quantitative and qualitative sense but may still have some relevance for our understanding of the general phenomenon of the Active Nucleus.

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