A POSSIBLE EVOLUTIONARY CONNECTION BETWEEN ACTIVE GALACTIC NUCLEI AND STARBURSTS IN LINERS

S. J. LEI,1,2 J. H. HUANG,1,2 W. ZHENG,3 L. JI,1,2 AND Q. S. GU1,2
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ABSTRACT

Our analysis of the two magnitude-limited samples of LINERs suggests a correlation between $L_{\text{FIR}}/L_{\text{B}}$, or $f(25 \mu m)/f(60 \mu m)$, and Hubble-type index at greater than 99.99% significance level. As $L_{\text{FIR}}/L_{\text{B}}$ and $f(25 \mu m)/f(60 \mu m)$ are considered to be indicators of star formation activity and active galactic nuclei (AGN) activity, respectively, our results suggest that LINERs with higher AGN activity may have a lower star formation contribution. The ones with highest AGN activity and lowest star formation contributions are elliptical galaxies. All well-studied type 1 LINERs belong to this group. On the other hand, LINERs with higher star formation activity present lower AGN contributions. We find all well-studied type 2 LINERs in this parameter space. Most LINERs having inner ring structures belong to this group. Statistics with other indicators of star formation or AGN activity (a nuclear mass-to-light ratio at the $H$ band and the ratio of X-ray to UV power) provide further evidence for such a trend. We have seen that along with the evolution of galaxies from late-type spiral galaxies to early-type ones and up to elliptical galaxies, the intensity of AGN activity increases with decreasing star formation contributions. The above analyses may suggest a possible connection between the host galaxies and nuclear activities, and it might also indicate a possible evolutionary connection between AGNs and starbursts in LINERs.

Subject headings: galaxies: active — galaxies: evolution — galaxies: nuclei — galaxies: Seyfert — galaxies: starburst

1. INTRODUCTION

It was the study of Simkin, Su, & Schwarz (1980) that revealed a more frequent occurrence of outer and inner rings in the host galaxies of Seyfert galaxies than those of non-Seyfert galaxies. This pioneering investigation of the possible connection between the host galaxies and nuclear activities has been confirmed recently (Hunt & Malkan 1999).

The galaxy morphology can be modified by environmental effects, such as mergers or interactions. It could be formed, on the other hand, as an evolutionary sequence (Martinet 1995), without galaxy interactions.

The role of minor mergers in the formation of active galactic nuclei (AGNs) has been tested by Corbin (2000). A very intriguing result obtained from this study is that the nuclear spectral type of galaxies is strongly dependent on their Hubble type instead of environmental effects, indicating the existence of a connection between the host galaxy and nuclear activity.

When Condon et al. (1982) suggested, and Rush, Malkan, & Edelson (1996) proceeded, to distinguish starbursts from AGNs by using the far-infrared (FIR)–radio correlation, a possible connection between the host galaxy and nuclear activity was involved. The nuclear spectral types of sources can be designated by their global properties. The FIR-radio correlation has proven a useful tool to successfully classify LINERs as type 1 and 2 in a recent investigation (Ji et al. 2000). Hunt & Malkan (1999), in their study of a small sample of LINERs, found that a higher frequency of inner rings in LINERs turned out to be related to type 2 LINERs.

It is worth exploring the astrophysical implication of this result, especially to understand a possible connection between the host galaxy and nuclear activity or even a possible connection between starbursts and AGNs in terms of the evolution of galaxies.

2. LINER SAMPLE

To facilitate the study of active nuclei and their hosts, it is desirable to utilize a LINER sample on the basis of host galaxy flux (Krolik 1999). One of the best samples in the literature is the spectroscopic survey by Ho, Filippenko, & Sargent (1997, hereafter HFS), from which we have a magnitude-limited LINER sample with a statistically meaningful size of 94.

A second, and deeper, magnitude-limited LINER sample has been constructed from a catalog of LINERs compiled by Carrillo et al. (1999, hereafter CMD), which is based on the criteria $m_h \leq 14.5$ and $\delta \geq 0^\circ$. The CMD sample contains 223 sources.

3. STATISTICAL RESULTS

3.1. Star Formation and AGN Activity

In order to test a possible connection between the host galaxies and nuclear activities, we need to study the star formation activity among LINER samples along with their AGN activity. As an indicator of star formation activity, the luminosity ratio $L_{\text{FIR}}/L_{\text{B}}$ has been widely used (Keel 1993; Huang et al. 1996; Hunt & Malkan 1999). On the other hand, the mid-infrared flux ratio $f(25 \mu m)/f(60 \mu m)$ has been known to be a good indicator of AGN activity (Hunt & Malkan 1999).

Following Hunt & Malkan (1999), we make plots of $f(25 \mu m)/f(60 \mu m)$ versus Hubble-type index for the HFS and CMD samples in Figures 1a and 1b, respectively. Significant correlations between them, greater than 99.99% for both the HFS and the CMD samples, imply a possible relation between nuclear activity and the evolutionary status of the galaxy, similar to the results obtained by Corbin (2000) and Hunt & Malkan (1999) for AGNs.

The different distributions shown in Figures 1a and 1b lie mostly in the lack of LINERs in late-type galaxies for the HFS...
sample, as compared with those for the CMD sample. It is something related to the selection effect in the HFS sample that makes it harder to find AGNs in late-type galaxies. Although the CMD sample is not complete for sources with \(12.5 < m_B \leq 14.5\), the situation is much improved. This selection effect may cause some problems in the study of the evolutionary status of AGN activity along the Hubble sequence. However, it is not crucial for our investigation, as the statistics given above indicated.

In Figure 2 we have shown the star formation indicator of \(L_{\text{FIR}}/L_B\) versus the Hubble-type index for the CMD sample only. The correlation is significant at a level greater than 99.99%. What the trend in Figure 2 shows is certainly consistent with the fact that the Hubble-type sequence is also a sequence of star formation rate (Kennicutt 1992). The most active star formation occurs in late-type spiral galaxies. In fact, the majority of LINERs with inner rings are located in this type (see Figs. 1 and 2).

### 3.2. Further Tests

There are other significant indicators for star formation or AGN activity, such as the nuclear mass-to-light ratio at the \(H\) band, \(M/L_H\), and the ratio of X-ray to UV power, \(\text{f}_{(2-10 \text{ keV})}/\text{f}_{(1300 \text{ Å})}\) (Oliva et al. 1999; Maoz et al. 1998).

A diagram of \(M/L_H\) versus \(f(25 \mu m)/f(60 \mu m)\) for Seyfert galaxies is shown in Figure 3a with the data obtained by Oliva et al. (1999), which again demonstrates the \(f(25 \mu m)/f(60 \mu m)\) ratio as a good indicator of AGN activity. The sources in the lower left side of the diagram are Seyfert 2 galaxies with circumnuclear starbursts, while those in the upper right side are Seyfert 1 galaxies without circumnuclear starbursts. The trend shown in Figure 3a might provide evidence for the evolutionary hypothesis for Seyfert galaxies (Hunt & Malkan 1999).

Following this approach, we made a similar plot for LINERs in Figure 3b, with the \(M/L_H\) data obtained by Devereux, Becklin, & Scoville (1987). The correlation between \(M/L_H\) and \(f(25 \mu m)/f(60 \mu m)\) is significant at the 97% level. Two sources shown with star symbols, NGC 1052 and NGC 4486, are those with the \(M/L_H\) data obtained by Oliva et al. (1999). The systematic difference between the two observations is obvious, as can be seen from different positions of the same object, NGC 1052.

Further evidence for this evolutionary trend might be provided using another AGN activity, i.e., the ratio of X-ray to UV power. As a result of the limited LINERs with both X-ray detections and UV observations, we use the \(Einstein\) data (CMD) for the X-ray fluxes instead of the hard X-ray fluxes used by Maoz et al. (1998). The UV fluxes are retrieved from the \(IUE\) archive data. The correlation between \(L_{\text{FIR}}/L_B\) and \(\text{f}_{(0.2-4.0 \text{ keV})}/\text{f}_{(1300 \text{ Å})}\) is shown in Figure 4, significant at the 99% level.

\[\text{Based on INES data from } IUE.\]
4. DISCUSSION

A key point in AGN unification hypotheses is to claim that Seyfert 1 and 2 galaxies are intrinsically similar and the different types of nuclear activity are caused by different viewing angles. Increasing evidence (Malkan et al. 1998; Hunt et al. 1999) suggests that Seyfert nuclei may be the same objects seen at a different evolutionary sequence. Seyfert 2 galaxies tend to reside in later morphological types than Seyfert 1 galaxies. Starbursts and massive stars play an important energetic role in a significant fraction of Seyfert 2 galaxies (Heckman 1999), while few Seyfert 1 galaxies have such circumnuclear starbursts (González Delgado et al. 1997; Hunt et al. 1997).

The data points in the lower right side of Figure 4 have a higher $\nu f(0.2–4.0 \text{ keV})/\nu f(1300 \text{ Å})$ ratio and a lower $L_{\text{FIR}}/L_{\text{B}}$ ratio; in other words, they have higher AGN activity and lower star formation contributions. It is the region where the well-studied LINERs with broad Hα emission or with active AGNs are located, e.g., NGC 3998, NGC 4486, and NGC 4594 (Larkin et al. 1998; Ho 1999; Nicholson et al. 1998; Maoz et al. 1998). We have found few LINERs with inner rings in this region. Sources with the highest AGN activity and the lowest star formation contributions are absolutely elliptical galaxies. It has been known that most X-rays detected in elliptical galaxies come from the extended halo where elliptical galaxies reside. Removing these elliptical galaxies from the sample used in Figure 4, the correlation between $L_{\text{FIR}}/L_{\text{B}}$ and $\nu f(0.2–4.0 \text{ keV})/\nu f(1300 \text{ Å})$ becomes significant at the 90% level.

On the contrary, the sources shown in the upper left side of the figure have a lower $\nu f(0.2–4.0 \text{ keV})/\nu f(1300 \text{ Å})$ ratio and higher $L_{\text{FIR}}/L_{\text{B}}$ ratio, i.e., lower AGN contribution and higher star formation activity. It is the region where some well-studied LINERs supported by massive stars are found, e.g., NGC 4569, NGC 4736, NGC 4826, NGC 5194 (Maoz et al. 1998; Larkin et al. 1998; Alonso-Herrero et al. 2000; Barth & Shields 2000).

The above argument holds for Figure 3b, too. The AGN-supported LINERs, NGC 1052, NGC 4579, NGC 4486, are distributed in the region with a higher $f(25 \mu \text{m})/f(60 \mu \text{m})$ ratio (strong AGN activity) and higher nuclear $M/L_{\text{B}}$ (small starburst contribution). However, NGC 7217, a well-studied starburst-supported LINER, is in the region having higher star formation activity and lower AGN contribution.

If adopting the Hubble sequence as an evolutionary sequence (Pfenniger, Combes, & Martinet 1994; Martinet 1995), the correlations in Figures 1 and 2 show that the AGN and the star formation activity are anticorrelated to the evolutionary status of galaxies. Along with the evolution from late-type spiral galaxies to early-type ones and up to elliptical galaxies, the intensity of AGN activity in LINERs increases with a decrease of star formation contributions, consistent with what the statistics performed for Figures 3 and 4 implied. Because of the large sample size used for Figures 1 and 2, more well-studied LINERs, AGN- or starburst-supported, can be found in their corresponding regions, e.g., starburst-supported LINERs NGC 404, NGC 3504, NGC 5055, and NGC 7743 (Maoz et al. 1998; Alonso-Herrero et al. 2000; Larkin et al 1998) and AGN-
supported LINERs NGC 2639, NGC 3718, NGC 4203, NGC 4278, and NGC 6500 (Alonso-Herrero et al. 2000; Ho 1999; Iyomoto et al. 1998; Shields et al. 2000; Falcke et al. 2000; Maoz et al. 1998). Probably, this evolutionary trend indicates processes in which massive black holes in LINERs are competing with the starbursts for the inflowing gas, a suggestion proposed by de Carvalho & Coziol (1999).

The LINERs residing in late-type spiral galaxies, with strong star formation and lower AGN activity, might be at an early evolutionary stage. They are type 2 LINERs. The growing bulges of galaxies are bound to be followed by the evolution of galaxies from late-type to early-type spiral galaxies. The formation of a massive black hole may turn out to be a natural evolution of the massive bulges of galaxies (Norman & Scoville 1988). Elliptical galaxies, S0 galaxies, and very early type spiral galaxies containing LINERs with broad Hα emission or active AGNs have massive bulges for the formation of massive or supermassive black holes (Wandel 1999; Magorrian et al. 1998), being active enough to suppress the circumnuclear starbursts in LINERs. These LINERs might be at a late evolutionary stage; they are type 1 LINERs.

In conclusion, the above analyses may suggest a possible connection between the host galaxies and nuclear activities and might also indicate a possible evolutionary connection between AGNs and starbursts in LINERs.

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