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Clues to the Nature of LINERs from their Hard X-ray Emission

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Abstract. We report X-ray properties of LINERs (low-ionization nuclear emission-line regions) obtained with *ASCA* and discuss the ionizing source in LINERs. X-ray spectra of most objects are represented by a two component model consisting of a soft thermal plasma and a hard component (power-law or thermal Bremsstrahlung). Observed X-ray luminosities are in the range between 4×10^{39} and 5×10^{41} ergs s^{-1}, which are smaller than or comparable to that of the "classical" low-luminosity Seyfert 1 galaxy NGC 4051.

We found that most LINERs with broad Hα emission in their optical spectra (LINER 1s) have a compact hard X-ray source and that the 2–10 keV X-ray luminosities are proportional to their Hα luminosities. This correlation strongly supports the hypothesis that the dominant ionizing source in LINER 1s is photoionization by hard photons from low-luminosity AGNs. Although some LINERs without broad Hα emission (LINER 2s) have X-ray properties similar to LINER 1s, the X-ray luminosities of most LINER 2s in our sample are lower than LINER 1s at a given Hα luminosity. The observed X-ray luminosities in these objects are insufficient to power their Hα luminosities, suggesting that their primary ionizing source is something other than an AGN, or that an AGN, if present, is obscured even at energies above 2 keV.

We define X-ray loud and quiet LINERs by $\log L_{\rm X}/L_{\rm H\alpha}$ greater than and smaller than unity, respectively. We found that X-ray quiet LINER 2s occupy a localized region with small [O I]/Hα on the excitation diagram by Veilleux and Osterbrock. Such a weak-[OI] LINER spectrum can be reproduced by photoionization by very hot stars. We suggest that the ionization source in X-ray quiet LINER 2s is a hot star cluster.

1. Introduction

LINERs (low-ionization nuclear emission-line regions; Heckman 1980) are fairly common in nearby galaxies. A recent optical spectroscopic survey of nearby galactic nuclei has shown that ∼30% of bright galaxies have LINERs (Ho, Filippenko, & Sargent 1997a,b; Ho et al. 1997c). The ionization mechanism of LINERs is still controversial (see Filippenko 1996 for a review), and there are several ionization mechanisms which can explain LINER type optical emission lines. These include (1) photoionization by low-luminosity AGNs (LLAGNs), (2) photoionization by very hot Wolf-Rayet stars or O-stars, (3) shocks, and (4) cooling flows.

Recent multiwavelength observations argue that a significant fraction of LINERs are genuine AGNs (e.g., Ho 1999a). Detection of an X-ray nucleus is one of the most convincing pieces of evidence for the presence of an AGN. From X-ray observations, the presence of LLAGNs in LINERs is reported for several objects (Ho 1999a; Terashima et al. 2000a, and references therein) and their luminosities ranges from 4×10^{39} to 5×10^{41} ergs s^{-1}, which is about 1–3 orders of magnitude lower than typical Seyfert galaxies. If such LLAGNs are the dominant ionizing source of the LINER-type emission lines, the optical emission-line luminosities are expected to be proportional to the luminosities of the ionizing photons from the LLAGNs. Indeed, a strong positive correlation between optical emission-line (Hα, Hβ, [O III]) luminosities and X-ray luminosities is observed for luminous AGNs (Elvis, Soltan, & Keel 1984; Ward et al. 1988; Mulchaey et al. 1994). Koratkar et al. (1995) reported that this correlation extends to intrinsically faint objects based on *ROSAT* observations of five low-luminosity Seyfert galaxies in the soft X-ray band. a small number of LINERs have been studied in the hard X-ray band, and a similar correlation is suggested (Halpern & Steiner 1983; Elvis et al. 1984).

The ionization mechanisms of LINERs, however, could be heterogeneous, and it is also possible that ionization sources other than AGNs are present. If other ionization mechanisms play a role, the X-ray luminosities are expected to be small compared to given optical emission-line luminosities (Pérez-Olea & Colina 1996).

In this paper, we present *ASCA* results of LINERs and examine the probable ionization mechanism in LINERs by comparing X-ray luminosities with Hα luminosities and optical emission-line ratios.

2. The Sample

We have systematically analyzed *ASCA* archival and proprietary data of LINERs in the bright galaxy sample of Ho et al. (1997a). We also analyzed low-luminosity Seyfert galaxies (hereafter referred as LLSeyfert) with log $L_{\mathrm{H}\alpha}$ < 41 ergs s^{-1} to compare their X-ray properties with those of LINERs and to discriminate between different ionizing sources in LINERs. Detailed results will be presented in the future paper (Terashima et al. 2000a). Results of *ASCA* observations for several objects have been already published, and references for them are summarized in Terashima et al. (2000b). We use only galaxies for which optical emission-line luminosities are published in the literature. Note that our sample is not complete and that some of the galaxies in our sample are selected based on large Hα fluxes (see Terashima et al. 2000c). Therefore, our sample is not an X-ray selected sample, and so it is not significantly biased toward X-ray bright objects. The galaxies in our sample are summarized in Table 1. Classifications are based on optical emission-line ratios (Ho et al. 1997a). Two objects (NGC 4192 and NGC 4569) are classified as transition objects between a LINER and an H II nucleus. We refer to objects with and without broad Hα emission as Type 1 (LINER 1s and LLSeyfert 1s) and Type 2 objects (LINER 2s and LLSeyfert 2s), respectively.

Table 1. The Sample

Class	Objects
LINER 1.9s	NGC 315, 1052, 3998, 4203, 4438, 4450, 4579
	NGC 4636, 5005
LINER 2s	NGC 404, 3507, 3607, 4111, 4192, 4261, 4374
	NGC 4457, 4569, 4594, 4736, 7217
Seyfert 1.0-1.9s	NGC 1097, 1365, 2639, 3031, 4258, 4565, 4639
	NGC 5033
Seyfert 2s	NGC 1386, 2273, 2655, 3079, 3147, 4501, 4941
	NGC 5194, 7743

3. ASCA Results of LINERs

X-ray emission is detected from all the objects except for the LINER 2 NGC 404 (*ROSAT* HRI detection of NGC 404 is reported by Komossa et al. 1999). The X-ray spectra of most of the objects are represented by a two-component model consisting of an optically-thin thermal plasma with a temperature of $\sim$0.7 keV and a hard component. Spectra of a few objects (NGC 4203 and 3998) do not require a soft thermal component. The hard component is well represented by a power law with a photon index of ~ 1.5–2.0 or thermal Bremsstrahlung with a temperature of several keV. The absorption column density for the hard component ranges from 10^{20} to 2×10^{23} cm^{-2}. Fe K lines are not detected from most LINERs except for clear detection from NGC 1052 and NGC 4579 and marginal detection from NGC 4261 and NGC 4736. Typical upper limits on the equivalent width of Fe K lines are 200–300 eV for bright objects and 1–2 keV for very faint objects such as some LINER 2s. The X-ray luminosities of LINERs are in the range from 4×10^{39} ergs s^{-1} to 5×10^{41} ergs s^{-1}.

The X-ray images in the hard band (above 2–4 keV) of LINER 1s (except for NGC 4636) are unresolved within the spatial resolution of *ASCA* (FWHM $\approx 0.5'$) and consistent with the LLAGN interpretation as the origin of hard X-rays. The hard-band images of some LINER 2s are also consistent with being point-like, while some objects (NGC 3607, 4111, 4374 and 4569) are extended compared to the point-spread function of XRT + SIS. Such extended images indicate that the hard X-ray emission from these objects is not dominated by an AGN.

In the next section, we will make use of the intrinsic luminosities of the hard component corrected for the absorption in the 2–10 keV band to compare with optical emission-line properties. If the absorption column density is greater than 10^{24} cm^{-2} and a transmitted hard X-ray continuum is not seen, corrections for the absorption are not made.

4. Ionizing Source in LINERs

4.1. LINER 1s

In order to examine whether optical emission lines in LINER 1s are photoionized by high-energy photons from an AGN, we search for a correlation between X-ray luminosities in the 2–10 keV band (L_{X}) and Hα luminosities ($L_{\mathrm{H}\alpha}$) for objects with broad Hα in their optical spectra. It is known that a significant positive correlation between these two quantities exists for luminous AGNs (e.g., Ward et al. 1988). If photoionization by an LLAGN is the dominant ionization mechanism in LINER 1s, a L_{X}-$L_{\mathrm{H}\alpha}$ correlation is expected. Figure 1 shows the correlation between L_{X} and $L_{\mathrm{H}\alpha}$ for LINER 1s and LLSeyfert 1s in our sample and luminous Seyfert 1s and QSOs taken from Ward et al. (1988); the Hα luminosities shown represent the sum of the narrow and broad components of the line. It is clear that the correlation extends to lower luminosities. This correlation strongly suggests that the dominant ionization source in LINER 1s is photoionization by LLAGNs with luminosities less than $\sim 5 \times 10^{41}$ ergs s^{-1}.

4.2. LINER 2s

The X-ray emission from LINER 1s is most likely dominated by AGNs. If LINER 2s are also LLAGNs, they might be obscured, by analogy with Seyfert 2s, and the X-ray continuum emission is expected to be absorbed by a large column density. On the other hand, other ionization mechanisms such as hot stars or shocks due to starburst

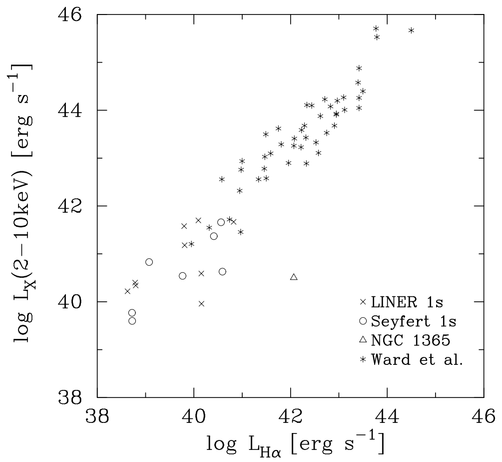

Fig. 1. X-ray–Hα luminosity correlation for LINER 1s and Seyfert 1s.

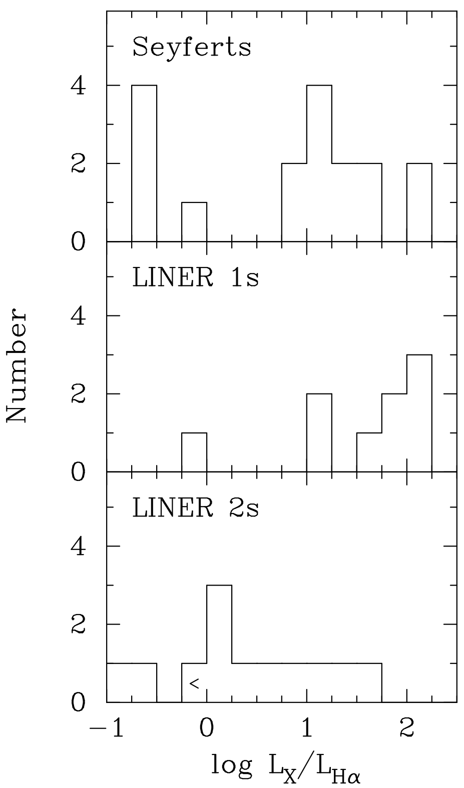

Fig. 2. $L_X/L_{H\alpha}$ luminosity ratio for LLSeyferts, LINER 1s and LINER 2s.

activity are expected to produce low values of $L_X/L_{H\alpha}$ compared to AGNs (Pérez-Olea & Colina 1996). In Figure 2, we compare the luminosity ratio $L_X/L_{H\alpha}$ for LINER 1s, LINER 2s, and LLSeyferts to examine whether the ionization mechanism in LINER 2s is the same as in LINER 1s and LLSeyferts; in this comparison we make use only of the narrow component of the Hα line. The mean of the $L_X/L_{H\alpha}$ distributions for LLSeyferts, LINER 1s, and LINER 2s, and are 30.2, 67.3, and 7.7, respectively. Thus the mean of $L_X/L_{H\alpha}$ for LINER 2s is about one order of magnitude smaller than those for LLSeyferts and LINER 1s. A few LINER 2s (NGC 4261, 4594 and 4736) have a $L_X/L_{H\alpha}$ ratio similar to LLSeyferts and LINER 1s, while many LINER 2s have a small $L_X/L_{H\alpha}$. Some LLSeyferts with small $L_X/L_{H\alpha}$ are most probably Compton thick objects in which only scattered X-rays are observed (NGC 1365, 1386 and 5194) since these objects have a strong Fe K emission line with an equivalent width of > 1 keV. Therefore, intrinsic $L_X/L_{H\alpha}$ values could be 1–2 orders of magnitude larger than observed.

If we assume a spectral energy distribution from UV to X-ray that is power-law shape with an index of −1 ($f_\nu \propto \nu^{-1}$; see Ho 1999b), log $L_X/L_{H\alpha}$ should be greater than 1.4 to drive Hα luminosities by photoionization under Case B recombination (Osterbrock 1989) and a covering fraction of unity. Since X-ray luminosities of LINER 2s are small ($L_X < 2 \times 10^{40}$ ergs s^{-1}), X-ray binaries in the host galaxy might also contribute to the observed X-ray fluxes. In fact, some objects have hard-band (>2 keV) images extending to several kpc (Terashima et al. 2000a, c), which implies an even lower value of $L_X/L_{H\alpha}$ for the nuclear component. Therefore, the objects with low log $L_X/L_{H\alpha}$ (<1) are too X-ray weak to ionize optical emission lines, even if X-ray variability of a factor of a few is taken into account. If an AGN is present and is the dominant ionizing source in these objects, it should be obscured even at energies above 2 keV. Although no clear evidence for the presence of heavily obscured AGN (e.g. heavily absorbed X-ray continuum and/or strong Fe K emission line) has been obtained so far, the current data cannot rule out such a possibility. Alternatively, there might be other ionization sources. The *Hubble Space Telescope* UV spectra of NGC 404 and NGC 4569 actually show a large number of hot stars concentrated in parsec-scale nuclear regions (Maoz et al. 1998), and these objects could be examples of LINERs ionized by stellar sources (Terashima et al. 2000c).

4.3. Optical Emission-Line Ratios and Ionizing Source in X-ray Loud and Quiet Objects

We divide our LINER sample into two classes by using the X-ray to Hα luminosity ratio. We define X-ray loud and quiet as objects with the ratio log $L_X/L_{H\alpha}$ greater than and less than unity, respectively. We examined the distributions of optical emission-line ratios on the excitation diagrams by Veilleux & Osterbrock (1987) for these two classes of objects. Figure 3 plots log $L_X/L_{H\alpha}$ versus log [O I]/Hα. The excitation diagram [O III]/Hβ versus [O I]/Hα is shown in Figure 4. It is intriguing that X-ray quiet objects are localized around the low [O I]/Hα ratio portion of the LINER classification on the [O I]/Hα versus [O III]/Hβ plot. Terashima et al. (2000c) reported that (X-ray quiet) LINER 2s have lower [O I]/Hα ratios based on an analysis of a small sample. This trend is also seen in the present sample. On the other hand, the [O I]/Hα

ratios of X-ray loud LINERs are widely spread. Terashima et al. (2000c) suggested that X-ray quiet LINER 2s with small [O I]/Hα are photoionized by hot stars because a LINER spectrum with small [O I]/Hα ratio is reproduced by photoionization by hot stars (Filippenko & Terlevich 1992; Shields 1992; Barth & Shields 2000). If X-ray quiet LINER 2s are ionized by a hidden AGN, [O I]/Hα should be widely spread like X-ray loud LINER 1s, X-ray loud LINER 2s, and Seyfert galaxies.

A similar trend is seen in the [S II]/Hα plot, but not clearly in the [N II]/Hα plot. The optical emission-line ratios of the X-ray quiet LINERs are in the range of the prediction of ionization by stellar sources. These facts support the interpretation that this class of objects is predominantly ionized by hot stars. Therefore, we conclude that hot stars are a significant source of ionization in X-ray quiet LINER 2s in our sample.

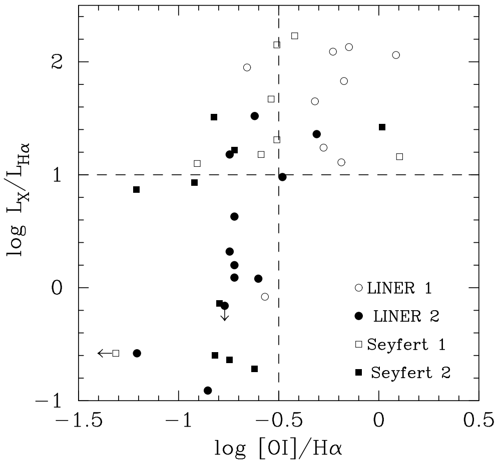

Fig. 3. Log $L_{\rm X}/L_{{\rm H}\alpha}$ versus log [O I]/Hα.

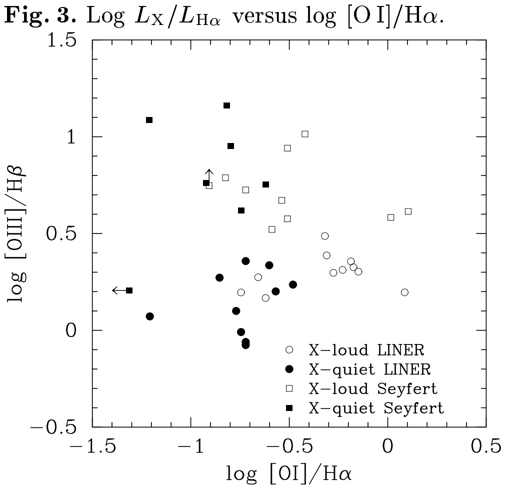

Fig. 4. Log [O III]/Hβ versus log [O I]/Hα diagram.

5. Fraction of AGNs in Bright Galaxies

According to the optical spectroscopic survey by Ho et al. (1997a, b), Seyferts, LINER 1s and LINER 2s are detected in 11%, 5%, 28% of northern ($\delta > 0°$) bright ($B_T \leq 12.5$ mag) galaxies. If we assume an extreme case that all Seyferts and LINER 1s are AGNs and all LINER 2s are not AGNs, the fraction of AGN is estimated to be 16% of bright galaxies. This percentage, however, should be regarded as a lower limit because extremely weak broad Hα is difficult to detect unambiguously (Ho et al. 1997c). Furthermore, some LINER 2s clearly indicate AGN-like activity. For example, NGC 4261 has prominent radio jets and kinematic evidence for a massive black hole (Ferrarese, Ford, & Jaffe 1996). Other examples include NGC 4594 and NGC 4736. The $L_{\rm X}/L_{{\rm H}\alpha}$ values for these object are similar to LINER 1s and LLSeyferts. This fact also indicates that the $L_{\rm X}/L_{{\rm H}\alpha}$ ratio is a good indicator of the presence of AGNs.

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