

LOW-LUMINOSITY AGN AND NORMAL GALAXIES

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ABSTRACT Low-luminosity AGN (with $L_X < 1 \times 10^{42}$ ergs s^{-1}) far outnumber ordinary AGN, and are therefore perhaps more relevant to our understanding of AGN phenomena and the relationship between AGN and host galaxies. Many normal galaxies harbor LINER and starburst nuclei, which, together with LLAGN, are a class of “low-activity” galaxies that have a number of surprisingly similar X-ray characteristics, despite their heterogenous optical classification. This strongly supports the hypothesis of an AGN-starburst connection. Further, X-ray observations of normal galaxies without starburst or AGN-like activity in their nuclei offer opportunities to study populations of X-ray binaries, HII regions, and warm or hot ISM under different conditions than is often the case in the Milky Way. The results of recent X-ray observations of these types of galaxies are reviewed, and what we hope to learn about both nearby and high redshift galaxies of each type from observations with forthcoming and planned satellites is discussed.

KEYWORDS: galaxies; abundances; galaxies:active; galaxies:starburst

1. INTRODUCTION

Since active galactic nuclei (AGN) comprise only a small fraction of all galaxies, it is more relevant for our general understanding of galactic processes to observe normal galaxies. With the availability of *imaged* X-ray observations, galaxies not necessarily dominated by a point source in their nucleus have now been studied in detail. This review will give an overview of these results, with an emphasis on galaxies exhibiting moderate or low amounts of activity in their nuclei.

In this paper, a low-luminosity AGN (LLAGN) is considered to be a galaxy with Seyfert-like optical spectra and an X-ray luminosity less than 10^{42} ergs s^{-1} . A starburst galaxy is a galaxy in which evidence of enhanced star-formation rates are observed, particularly in kpc-sized nuclear regions. Most often this is observed by the presence of HII-region like optical emission lines, however other signs include high IR luminosities (i.e., $L_{IR} > 10^{10} L_{\odot}$; c.f., Telesco 1988). In LINER galaxies the optical emission lines are observed with line diagnostic ratios that differ from both starburst and LLAGN ratios. The most likely scenarios for the ionization flux in LINERs are a LLAGN (albeit with different physical properties than LLAGN with Seyfert-like spectra), shocks (Dopita et al. 1996) and hot stars (c.f., Shields 1992). Interestingly, 15% of LINERs exhibit *broad* $H\alpha$ emission (Ho, Filippenko, Sargent, & Chen 1997). These “LINER 1” galaxies are almost certainly LLAGN, and the

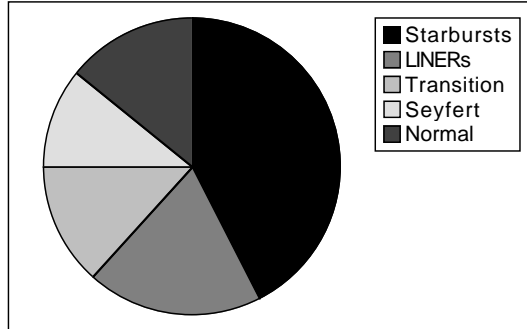


FIGURE 1. Demographics of activity in nearby galaxies.

fact that the ratio of LINER 1 to LINER 2 galaxies is similar to the fraction of Seyfert 1/Seyfert 2 galaxies is suggestive that most LINERs are indeed LLAGN.

1.1. Demographics

In order to properly assess the prevalence of LLAGN, LINER and starburst activity, it is necessary to perform a careful survey of nearby galaxies in which the galactic light is subtracted from the nuclear spectrum in order for the often-weak optical emissions line to be detected. Such a survey was recently completed by Ho, Filippenko & Sargent (1997). The demographics of these types of activity is shown in Figure 1. Clearly, “low-activity” galaxies (starburst, LINER, and LLAGN, and transition nuclei containing both LLAGN and starburst emission), 86% of the total, dominate over “normal” galaxies. Furthermore, “normal” AGN only comprise $\sim 10\%$ of all galaxies (Ho, Filippenko, & Sargent 1997). This emphasizes the importance of studying these types of galaxies: the usual state of affairs is for a galaxy to exhibit starburst or LLAGN activity (or both) in its nucleus, and most AGN in the local universe are in a low-luminosity state.

2. NORMAL GALAXIES

In elliptical/early-type galaxies the X-ray emission is dominated by hot gas (in some cases similar to group or cluster of galaxies X-ray emission, with a King-like radial surface brightness profile, occasionally including a cooling flow), with a temperature of $0.8 - 1.0$ keV (Trinchieri, Fabbiano, & Kim 1998). Some early-type galaxies also contain a contribution from a LLAGN (see Di Matteo, et al.; these proceedings) and low-mass X-ray binaries (LMXB, Irwin & Bregman, 1998).

The X-ray emission of spiral galaxies is generally dominated by X-ray binaries (Fabbiano 1989). Spiral arms often contain HII regions, particularly regions of local density enhancements (i.e., knots). These HII regions are often X-ray bright as a result of the products of enhanced star formation: hot stars, supernovae (SN) and

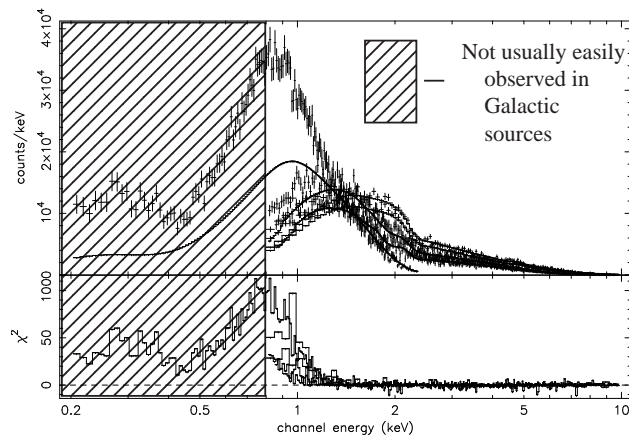


FIGURE 2. ASCA + PSPC spectra from the bulge of M31. Figure taken from Irwin & Bregman (1999), with a shaded area added to delineate the region typically absorbed in Galactic X-ray sources.

supernova remnants (SNR), high-mass X-ray binaries and black hole candidates (BHC) (c.f. NGC 1313 in Colbert et al. 1997). Not surprisingly, “bluer” galaxies, which tend to be later-type galaxies with higher star-formation rate (with the blue colors being a result of a higher proportion of massive stars than is observed in galaxies dominated by older stellar populations) are X-ray bright (Fabbiano, Feigelson, & Zamorani 1982). There is also a strong correlation between X-ray luminosity and IR luminosity, with the IR emission being produced by dust that has been heated by massive stars (David, Jones & Foreman 1992; Green, Anderson & Ward 1992). In cases of very high star formation rates occurring near the edge of galaxies, blow-outs can occur when the local pressure resulting from outflows from hot stars and SN exceeds the ambient interstellar medium (ISM) pressure, as observed by ROSAT in galaxies such as NGC 55 (Schlegel et al. 1997). There is also X-ray evidence that normal galaxies (Cui et al. 1996), including the Milky Way, possess hot ($T \sim 10^6\text{K}$) “halos” or “coronae” (Spitzer 1956).

Spiral galaxies also typically contain a bulge component, which may be counterparts to elliptical galaxies. A substantial fraction of the X-ray sources found in the nearest spiral galaxy, M31, are concentrated in the bulge. These sources are presumably mostly LMXB associated with the older stellar populations in globular clusters. The X-ray spectrum of the bulge region of M31 as observed by the ROSAT PSPC and ASCA (Irwin & Bregman 1999) and BeppoSAX (Trinchieri et al. 1999). This spectrum has a power-law component consistent with X-ray binaries in our galaxies, plus a soft component (see Figure 2) that is similar to that considered to be due to X-ray binaries in early-type galaxies. Note that it would be difficult to observe this soft component in Galactic binaries since most lie in the disk of the Milky Way and hence are highly absorbed.

Colbert and Mushotzky (1999) discuss a survey of X-ray sources in normal

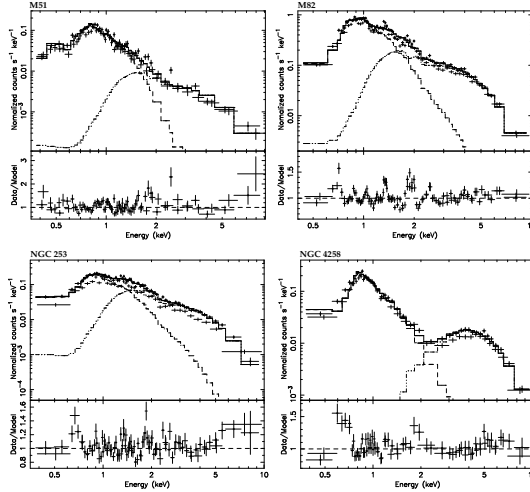


FIGURE 3. ASCA SIS spectra of M51 (starburst + LLAGN), M82 (starburst), NGC 253 (starburst) and NGC 4258 (LLAGN).

galaxies with luminosities in excess of $1.3 \times 10^{38} \text{ ergs s}^{-1}$, the Eddington luminosity for accretion onto a solar-mass object. These intermediate-luminosity X-ray objects (IXO) have X-ray spectra consistent with accretion onto black holes with masses of $\sim 10^{1-4} M_{\odot}$. IXOs are typically significantly displaced from the galactic centers, and hence they are not AGN. This implies that IXOs may be cases of “intermediate” mass black holes, and may be precursors to some modern-day AGN (see also M82 below and in Ptak & Griffiths 1999).

3. LOW-ACTIVITY GALAXIES

3.1. Spectral Properties

Despite their heterogeneous optical classification, low-activity galaxies usually have a similar spectral shape (Serlemitsos, Ptak & Yaqoob 1996). Specifically, in general these galaxies exhibit at least two spectral components: a soft, thermal component with $kT \sim 0.7 \text{ keV}$ and a hard component well-modeled by either a thermal bremsstrahlung with $kT \sim 5 - 10 \text{ keV}$ or a power-law with $\Gamma \sim 1.8$ (Ptak et al. 1999). The hard (soft) component is typically absorbed by a column density of $\sim 10^{22} \text{ cm}^{-2}$ ($\sim 10^{20-21} \text{ cm}^{-2}$). The fact that the hard component tends to be more spatially compact (see below) and absorbed than the soft component implies that the hard component is emanating from further within the galaxies (i.e., the nuclei). The fact that starburst galaxies exhibit a hard component, likely due accreting sources, and LINER and LLAGN galaxies exhibit soft emission, likely due to starburst activity, strongly supports the idea of a starburst/AGN connection.

The luminosity of the hard component tends to be on the order of 10^{40-41} ergs s^{-1} and the luminosity of the soft component 10^{39-40} ergs s^{-1} , with the relative intensity varying from galaxy to galaxy (see Figure 3). It is evidently rare for starburst activity, the origin of the soft component, to achieve luminosities in excess of 10^{40-41} ergs s^{-1} (Halpern, Helfand, & Moran 1995; however see Moran, Lehnert & Helfand 1999 for a counter-example in NGC 3256). Accordingly, sources with X-ray luminosities $> 10^{41}$ ergs s^{-1} (e.g., NGC 3998 and NGC 3147) only require a power-law component since the starburst component is overwhelmed. Conversely, in Seyfert 2s where the AGN is highly absorbed, starburst emission is often observed below 2 keV (see Turner et al. 1998).

The abundances inferred from the soft component tend to be sub-solar (on the order of 10^{-1} solar). This is surprising since starburst emission is presumably the result of massive star evolution and accordingly should be highly enriched, however many effects might be contributing to this. For example, it is probably too simple to be fitting the multi-temperature starburst emission with a single component (c.f., Breitschwerdt & Komossa 1999; Dahlem, Weaver & Heckman 1998), or other sources of continuum may be present such as soft emission from X-ray binaries (c.f., Figure 2). In brighter sources (see the residuals in Figure 3 and Ptak et al. 1997), it appears that there is a deficiency of Fe relative to α -process elements (e.g., Ne, Mg, Si, S, etc. produced in massive stars), although the effect is diminished somewhat when more complex models are invoked (see Dahlem, Weaver, & Heckman 1999).

3.2. Fe-K Emission

Fe-K emission is an important diagnostic in AGN studies since its energy, physical width, and equivalent width (EW) are functions of the physical conditions in the accretion region. In the case of an obscured nuclear region, the EW of an Fe line is expected to be greatly enhanced since the direct continuum is diminished. Although most low-activity galaxies are too faint for Fe-K to be detected, in several cases Fe-K is detected and is often complex. For example, the Fe-K EW in NGC 3147 (Ptak et al. 1996), NGC 1365 (Iyomoto et al. 1997), M51 (Terashima et al. 1998a), NGC 4736 (Roberts, Warwick, & Ohashi 1999) and NGC 1052 (Weaver et al. 1999) are high (> 100 eV) relative to Seyfert 1 EW values ($\sim 100 - 200$ eV; Nandra et al. 1997), consistent with an obscured nucleus. In M81, the Fe-K line appears to contain several components or may be broad, possibly due to an accretion disk (Ishisaki et al 1996; Serlemitsos, Ptak & Yaqoob, 1996). NGC 4579 (Terashima et al. 1998b; Terashima et al. 2000ab) is a particularly interesting case where the line was observed to be due to *ionized* material in a 1995 ASCA observation, but was observed to be due to neutral material in 1998.

(Ionized) Fe-K emission was detected marginally by ASCA in M82 (Ptak et al. 1997) and in M82 and NGC 253 significantly by BeppoSAX (Cappi et al. 1999). This emission strongly suggests that very hot gas ($T \sim 10^8$ K) is present in these starburst galaxies. However, the EW of the Fe-K lines is only on the order of $100 - 200$ eV, considerably less than that expected from solar-abundance hot gas (EW ~ 600 eV).

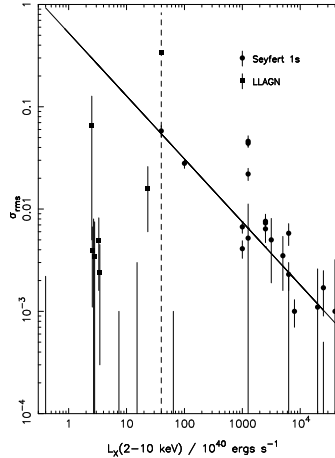


FIGURE 4. The trend of “excess variance”, a measure of short-term variability, with X-ray luminosity in Seyfert 1s and low-activity galaxies, from Ptak et al. (1998).

Again, the Fe abundance may be depressed in these galaxies, however it is also likely that other sources of continuum are present, diluting the thermal Fe-K emission.

3.3. Temporal Properties

Low-activity galaxies tend to vary on long (months to year) time scales (c.f., M81 in Ishisaki et al. 1996; NGC 4579 in Serlemitsos, Ptak & Yaqoob 1996), but not on short time scales as observed in Seyferts (Ptak et al. 1998; however note that M81 has been observed to vary at the 30% level on day time scales; Pellegrini et al. 2000). Surprisingly, some of the most variable low-activity galaxies have been starbursts. For example, the nuclear source in the starburst NGC 3628 “shut off”, varying by a factor of ~ 40 (Dahlem, Heckman, & Fabbiano 1995), and M82 has varied considerably in the 2-10 keV bandpass (Ptak & Griffiths 1999; Matsumoto & Tsusru 1999; Gruber et al., these proceedings). This implies that at least some of the contribution to the hard component in starburst galaxies is due to accreting sources. The lack of variability on short times scales is demonstrated in Figure 4. As argued in Ptak et al. (1998), this marked break from the temporal behavior of Seyfert 1s implies a large source extent for the X-ray producing regions in low-activity galaxies. While in some cases this might be due to a multiple sources of X-ray emission, it may also be due to the prevalence of advection-dominated accretion disks, in which the entire disk contributes to the X-ray emission, as opposed to the “ α ”-disks in Seyferts in which the X-rays are most likely produced by flares. On the other hand, the short-term variability observed in M82 may be our first look at the hard X-ray light curve of an IXO, assuming that the source of the 2-10 keV variability is the off-nuclear point source observed by the ROSAT HRI (Collura et al. 1994).

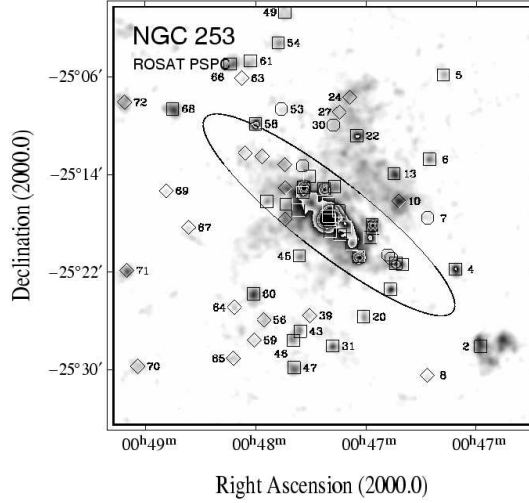


FIGURE 5. ROSAT PSPC image of NGC 253, from Vogler & Pietsch (1999).

3.4. Spatial Properties

Spatially most low-activity galaxies have 2-10 keV emission which is concentrated in the nucleus (see Ptak 1997, although the statistics are limited in many cases) and are extended over kpc scales in addition to being concentrated in multiple point sources. This tends to be particularly true of starburst galaxies (c.f., Read, Ponman, & Strickland 1997; Dahlem, Weaver, & Heckman 1998) but these phenomena are also seen in LINERs and LLAGN (c.f., the LINER NGC 4594 in Fabbiano & Juda 1997; the LINER NGC 3079 in Pietsch, Trinchieri, & Vogler 1998; the LLAGN M51 in Marston et al. 1995, and the LLAGN NGC 4258 in Cecil, Wilson, & De Pree 1998). In one of the nearest starburst galaxies NGC 253 (at ~ 2.5 Mpc), ~ 73 point sources (some of which are background QSOs) have been detected by ROSAT (Vogler & Pietsch 1999; see Figure 5), in addition to the extended emission associated with the nuclear region, disk, and halo of NGC 253. Interestingly, the point source distribution in NGC 253 is consistent with that of M31 (with the older-population buldge sources removed) and M33 (Figure 6). A similar result is observed more generally by Roberts et al. (these proceedings), which provides motivation that a *universal* luminosity distribution of X-ray binaries can be found, and the high-luminosity end of which would be the IXOs.

4. CONCLUSIONS AND FUTURE PROSPECTS

Both “normal” galaxies and low-activities provide very rich data sets for studying phenomena that is difficult to study in the Milky Way (i.e., due to extinction) and/or is not present in the Milky Way (i.e., starburst regions with very high star

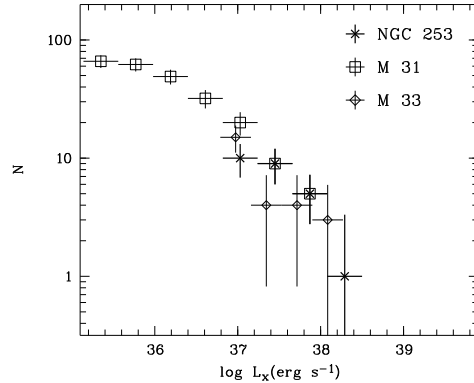


FIGURE 6. The luminosity distribution of point sources in NGC 253, M33 and M31 (excluding buldge sources), from Vogler & Pietsch (1999).

formation rates resulting in superwinds). The X-ray emission occurs in both point sources, which tend to be the most luminous known X-ray binaries and supernovae, and in complex diffuse emission that is the result of heating of the ISM by hot star, supernovae and, in some cases, superwind outflows. The brightest X-ray binaries (IXOs) are black hole candidates that potentially have masses on the order of $10^{1-4} M_{\odot}$, intermediate to that of Galactic BHC and AGN. Both starburst and accretion emission tend to be observed whenever either type of activity is present, strongly supporting the notion of a starburst/AGN connection. There appears to be a natural upper-limit to the luminosity of starburst processes on the order of 10^{41} ergs s^{-1} , and so starburst emission is usually overwhelmed by AGN emission that is not absorbed and exceeds $L_X \sim 10^{42}$ ergs s^{-1} . Observed abundances tend to be absurdly low, but that is almost certainly due to “contamination” of the continuum from multiple temperature gas emission and unresolved point sources. Chandra and XMM will be able to resolve the starburst emission spatial and extract CCD resolution spectra, which will resolve this issue and allow abundance and temperature enhancements to be observed in individual regions within the galaxies.

The X-ray properties of nearby normal and low-activity galaxies suggest that they will contribute less $\sim 10\%$ of the X-ray background (c.f., Griffiths & Padovani 1991; Yaqoob et al. 1995). This fraction can increase if these galaxies become harder and more luminous at earlier epochs, i.e., due to the enhanced starburst activity associated with the peak in the star formation history of the universe at redshifts of $\sim 1 - 2$ (Hughes et al. 1998). It may be possible to directly observe evolution in low-activity galaxies with ultra-deep XMM surveys or with telescopes such as XEUS that promise effective areas on the order of m^2 (see Figure 7).

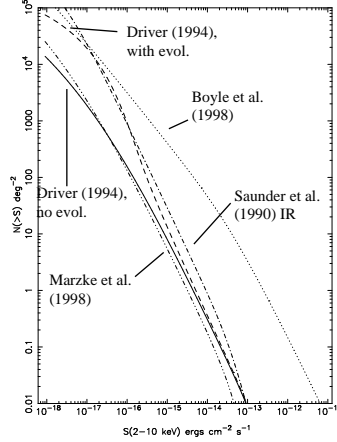


FIGURE 7. The expected $\log N$ - $\log S$ distributions in the 2-10 keV bandpass obtained by converting the optical luminosity functions of Driver (1994) and the IR luminosity function of Saunders et al. (1990) to the X-ray bandpass using the optical and IR to X-ray correlations of David, Jones & Forman (1992) and Green, Anderson, & Ward (1992), respectively. Note that for the mean power-law spectral slope of low-activity galaxies described in Ptak et al. (1999) of $\Gamma \sim 1.7 - 1.8$, $F_{2-10 \text{ keV}} = F_{0.5-4.0 \text{ keV}}$.

REFERENCES

- ??reitschwerdt, D. & Komossa, S. 1999, Ap&SS, in press
 ??appi, M. et al. 1999, A&A, 350, 777
 ??ecil, G., Wilson, A., & De Pree, C. 1995, ApJ, 440, 181
 ??olbert, E. et al. 1995, ApJ, 446, 177
 ??olbert, E., & Mushotzky, R. 1999, ApJ, 519, 89
 ??ollura, A., Schulman, E., Reale, F., & Bregman, J. 1994, ApJ, 420, L63
 ??ui, W., Sanders, W., McCammon, D., Snowden, S., & Womble, D. 1996, ApJ, 468, 102
 ??avid, L., Jones, C., Forman, W. 1992, ApJ, 388, 82
 ??ahlem, M., Heckman, T., & Fabbiano, G. 1995, ApJ, 442, 49L
 ??ahlem, M., Weaver, K., & Heckman, T. 1998, ApJS, 118, 401
 ??opita, M., Koratkar, A., Evans, I., Allen, M., Bicknell, G., Sutherland, R., Hawley, J., & Sadler, E. 1996, in "The Physics of LINERS", ASP Conference Series, Vol. 103, ed. M. Eracleous, A. Koratkar, C. Leitherer, and L. Ho, p.44
 ??river, S. 1994, Ph.D. thesis, University of Wales
 ??abbiano, G., Feigelson, E., Zamorani, G. 1982, ApJ, 256, 397
 ??abbiano, G. 1989, ARA&A, 27, 87
 ??abbiano, G. & Juda, J. 1997, ApJ, 476, 666
 ??reen, P., Anderson, S. & Ward, M. 1992, MNRAS, 254, 30
 ??riffiths, R. & Padovani, P. 1990, ApJ, 360, 483

??alpern, J., Helfand, D., & Moran, E. 1995, ApJ, 453, 61
 ??o, L., Filippenko, A., Sargent, W. 1997, ApJ, 487, 568
 ??o, L., Filippenko, A., Sargent, W., Peng, C. 1997, ApJS, 112, 391
 ??ughes, D. et al. 1998, Nature, 395, 47
 ??rwin, J. & Bregman, J. 1999, ApJ, 527, 125
 ??shisaki, Y. et al. 1996, PASJ, 48, 237
 ??yomoto, N., Makishima, K., Fukazawa, Y., Tashiro, M., & Ishisaki, Y. 1997, PASJ, 49, 425
 ??arston, A. et al. 1995, ApJ, 438, 663
 ??arzke, R., Da Costa, L., Pellegrini, P., Willmer, C., & Geller, M. 1998, ApJ, 503, 617
 ??atsumoto, H. & Tsuru, T. 1999, PASJ, 51, 321
 ??oran, Lehnert, & Helfand 1999, ApJ, 526, 649
 ??andra, K., George, I., Mushotzky, R., Turner, T. & Yaqoob, T. 1997, ApJ, 476, 70
 ??ellegrini, S. et al. 2000, A&A, 353, 447
 ??ietsch, W., Trinchieri, G., & Vogler, A. 1998, A&A, 340, 351
 ??tak, A., Yaqoob, T., Serlemitsos, P., Kunieda, H. & Terashima, Y. 1996, ApJ, 459, 542
 ??tak, A., Serlemitsos, P., Yaqoob, T., & Mushotzky, R. 1997, AJ, 113, 1286
 ??tak, A. 1997, Ph.D. Thesis, The University of Maryland
 ??tak, A., Yaqoob, T., Mushotzky, R., Serlemitsos, P. & Griffiths, R. 1998, ApJ, 501, L37
 ??tak, A., Serlemitsos, P., Yaqoob, T., & Mushotzky, R. 1999, ApJS, 120, 179
 ??tak, A. & Griffiths, R. 1999, ApJ, 517, 85L
 ??ead, A., Ponman, T. & Strickland, D. 1997, MNRAS, 286, 626
 ??aunders, W. et al. 1990, MNRAS, 242, 318
 ??chlegel, E., Barrett, P., & Singh, K. 1997, AJ, 113, 1296
 ??erlemitsos, P., Ptak, A., & Yaqoob 1996, in "The Physics of LINERS", ASP Conference Series, Vol. 103, ed. M. Eracleous, A. Koratkar, C. Leitherer, and L. Ho, p.70
 ??hields, J. 1992, ApJ, 399, 27L
 ??pitzer, L. 1956, ApJ, 124, 20
 ??elesco, C. 1988, ARA&A, 26, 343
 ??erashima, Y. et al. 1998a, ApJ, 496, 210
 ??erashima, Y. et al. 1998b, ApJ, 503, 212
 ??erashima, Y. et al. 2000, ApJ, 535, 79L
 ??rinchieri, G. et al. 1999, A&A, 348, 43
 ??rinchieri, G., Fabbiano, G., & Kim, D. 1997, A&A, 318, 361
 ??ogler, & Pietsch, W. 1999, A&A, 342, 101
 ??eaver, K., Wilson, A., Henkel, C. & Braatz, J. 1999, ApJ, 520, 130
 ??eaver, K., Heckman, H. & Dahlem, M. 2000, ApJ, 534, 684
 ??aqoob, T. et al. 1995, ApJ, 455, 508