X-RAY PROPERTIES OF GALACTIC NUCLEI

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Preparing this review was my just punishment for stating only two years ago - in another review (Weedman 1977) - that Seyfert galaxies are not strongX-ray sources. I said that because, as recently as three years ago, NGC 4151 was the only Seyfert galaxy known as an X-ray source. Now we have 36 Seyfert 1 galaxies, along with 12 other galaxies with strong emission-line nuclei, that are X-ray sources. And this is all without even having HEAO-2 data at our disposal yet. The study of active galactic nuclei with X-ray astronomy is progressing so rapidly that a reviewer feels almost hopeless. The best I can do is summarize what is known as of the summer of 1979 and give a simple overview of how X-ray and other properties relate.

Some excellent reviews of the X-ray properties of Seyfert and other emission-line galaxies already exist. I especially recommend that by Andrew Wilson (1979). He provides very complete references as of a year ago, but X-ray astronomy is progressing so rapidly that he then had only somewhat more than half the active nuclei now in Tables 1 and 2. It was the group working with the Ariel V SSI that made the initial comprehensive X-ray studies of Seyfert galaxies (Ward et al. 1977, Elvis et al. 1978). The UHURU results for Seyfert galaxies followed soon after and are summarized by Tananbaum et al. (1978); the HEAO-A-2 survey results are now in press (Marshall et al. 1979) I have tried to incorporate these and other recent results in Tables 1 and 2.

The last few yars have also seen an enormous increase in the amount of other data for Seyfert galaxies. The greatest optical effort has been by Osterbrock and collaborators at Lick Observatory (the most recent summary and review of the work is by Osterbrock 1979). Comprehensive spectrophotometric data is also being published by de Bruyn and Sargent (1978). A compilation of infrared results was recently published by Rieke (1978), and a thorough study of the radio properties is given by de Bruyn and Wilson (1978). We seem almost to the point of knowing everything we want to about Seyfert galaxies - except the explanation of why they exist at all!

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Table 1

Seyfert 1 Galaxies Known as X-ray Sources

Galaxy	Position	Flux	L(x-ray)	cz	x-ray/Hβ	References
Mkn 335	0003+199	2.9	43.86	7500	1.5,1.4	1
III Zw 2	0008+107	4.9	45.20	26930	2.2,1.9	2,4,
ESO 113-IG45	0122-591	2.5	44.34	13830	1.0	5
NGC 526A	0123-352		43.65	5400		6,17
Mkn 590	0212-010	3.8	44.05	8100		2
NGC 931	0227+312			4910		7,8
Mkn 372	0246+191	3.0	44.07	9300		2
3C 120	0430+053	5.8	44.41	9900	2.1	1
Akn 120	0514-002	1.9	43.92	9900		1
MCG 8-11-11	0551+464	4.9	43.92	6150		1,2,3,9
Mkn 376	0711+458	3.1	44.59	16800	2.0,1.8	3
Mkn 79	0739+499	3.2	43.79	6580	1.7,1.5	1,3
Mkn 142	1022+519	2.8	44.36	13500	2.5	2
Mkn 40	1123+546	3.3	43.75	6150		1
NGC 3783	1136-375	4.7	43.20	2740	1.8	1,2,3,9
NGC 4151	1208+397	11	42.68	990	1.2	1,2,3,9
NGC 4593	1238-052	5.1	43.18	2560		2,8
X Comae	1259+287			27600		10
MCG 6-30-15	1332-336	6.3	42.93	1800		2,11
IC 4329A	1346-300	6.1	43.67	4140	2.0	1,3,12,14
Mkn 279	1352+695	4.6	44.24	9220	2.3,1.7	3
Mkn 464	1354+388	3.7	44.59	15300		2,8
NGC 5548	1416+256	4.2	43.67	4990	1.8,1.5	1,2,3,9
Mkn 876	1614+658		45.0	38700		8
3C 382	1833+326	5.3	44.87	17580	2.3,2.0	2,8,13
ESO 140-G43	1840-626	3.5	43.43	4150		2
ESO 103-G35	1834-653	4.1	43.45	3900		2
3C 390.3	1846+797	3.0	44.60	17100	2.4,2.1	1,2,13
ESO 141-G55	1917-587	2.9	44.20	11030	1.2	2,3,9,5
NGC 6814	1940-106	4.6	42.72	1590		2,3,9
Mkn 509	2041-109	4.1	44.32	10650	1.7,1.2	1,2,3,9
NGC 7213	2208-473	3.2	42.64	1740		8,2
Mkn 304	2215+140	3.3	44.77	19950	1.9,1.8	1
NGC 7469	2301+086	5.2	43.77	5020	1.7,1.4	1
MCG 2-58-22	2302-090	5.6	44.72	14380	1.4	5
Mkn 541	2354+073	1.2	43.91	12300	2.3	1
		mean =	43.96			

References are 1) Tananbaum et al. (1978), 2) Marshall et al. (1979), 3) Elvis et al. (1978), 4) Schnopper et al. (1978a), 5) Ward et al. (1978), 6) Griffiths et al. (1979a), 7) Ward and Wilson (1978), 8) Dower et al. (1979), 9) Mushotzky et al. (1979), 10) Ku et al. (1979), 11) Pineda et al. (1979), 12) Wilson and Penston (1979), 13) Marshall et al. (1978), 14) Delvaille et al. (1978), 15) Griffiths et al. (1979b), 16) Bradt et al. (1978), 17) Ward et al. (1979), 18) Schnopper et al. (1978b).

Flux given is the mean 2-10 keV flux in units of 10^{-11} ergs cm^{-2} s^{-1}, derived assuming 1 UHURU count = 2.4 x 10^{-11} ergs cm^{-2}; 1 Ariel V(SSI) count = 5.1 x 10^{-11} ergs cm^{-2}; 1 HEAO-A2 count = 3 x 10^{-11} ergs cm^{-2}. L(x-ray) is log of x-ray luminosity, assuming H_o = 50 km s^{-1}Mpc^{-1}; x-ray/Hβ is log of ratio L(x-ray) to L(Hβ). Two values compare Hβ measures from Weedman (1976) with those deduced using equivalent widths from Osterbrock (1977) and continuum fluxes from deBruyn and Sargent (1978).

From results of the Ariel V and UHURU work, it is clear that the X-ray detection of a Seyfert galaxy correlates well with the optical classification as Seyfert 1 (Elvis et al. 1978, Tananbaum et al. 1978). The optical classification depends only on the presence of broad Balmer emission lines. Regardless of the eventual details of this correlation, it is important because it shows the X-ray luminosity in the largest class of X-ray galaxies - the Seyfert 1 - is somehow associated with the broad Balmer lines. This is further reflected in a tendency for the maximim Balmer-line width to scale with X-ray luminosity (Wilson 1979). These correlations provide important support to models for these nuclei that place the broad-line region close to the ultimate energy source. Osterbrock (1978), for example, has defended a model in which the broad lines are associated with a rotating accretion disk. For these reasons, I have chosen to use the Hβ line fluxes in making comparisons between optical and X-ray properties of galactic nuclei.

A summary of the information in Tables 1 and 2 is presented in Figure 1. This figure illustrates most of the things that should be emphasized about this collection of galactic nuclei:

a) The Seyfert 1 galaxies already known cover a wide range of X-ray luminosities, approaching a factor of 1000.

b) These luminosities overlap those of quasars, the fainter quasar in Figure 1 being MR2251-178 (Canizares et al. 1978) and the brighter 3C273 (Worrall et al. 1979).

c) There is substantial scatter in the ratio L(X-ray)/L(Hβ). The figure caption explains the large uncertainties in the Hβ measures, but these by no means explain the scatter. Nor would the known X-ray variability be a sufficient cause. It appears that this intrinsic (X-ray)/Hβ ratio can vary by a factor of ten from object to object. Formally, the mean value in the log of this ratio for all Seyfert 1 is 1.79 ± 0.4.

d) Galactic nuclei not Seyfert 1 have systematically fainter X-ray luminosities, on average by a factor of 10. This is clear from comparing Tables 1 and 2. Determining the nature of these objects and their relation to Seyfert 1 is of high priority.

Continuing with our first-order consideration of what is known about these sources, we now examine the luminosity function of X-ray Seyfert 1. This has been done by Elvis et al. (1978), Tananbaum et al. (1978) and Mushotzky et al. (1979) using various completeness assumptions. It is important to determine because X-ray galaxies may account for a significant fraction of the X-ray background.

The surveys from UHURU, Ariel V and HEAO A-2 provide all sky coverage. Therefore, the Seyfert 1 galaxies in Table 1 already represent the apparently brightest in the entire sky. As long as their distances are known, a luminosity function can be calculated simply. This is done by noting how large a volume of space has to be surveyed until a Seyfert 1 of a given luminosity is found. Such volumes are determined using luminosities and redshifts in Table 1. A luminosity-redshift

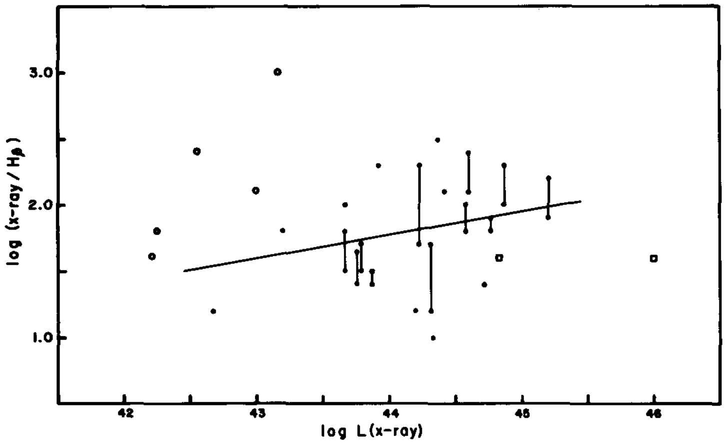

Figure 1: Ratio of X-ray to Hβ flux as a function of X-ray luminosity (2-10 keV assuming $H_0 = 50$ km s^{-1} Mpc^{-1}).
Squares are quasars 3C 273 and MR 2251-178; filled circles are Seyfert 1; open circles are other galaxies. Separate measures of same object (table 1) illustrated by connected points, which give estimate of uncertainty in Hβ measures for Seyfert 1. Uncertainty arises primarily from systematic differences in defining broad line wings and continuum. The line is a least-squares fit to Seyfert 1 points.

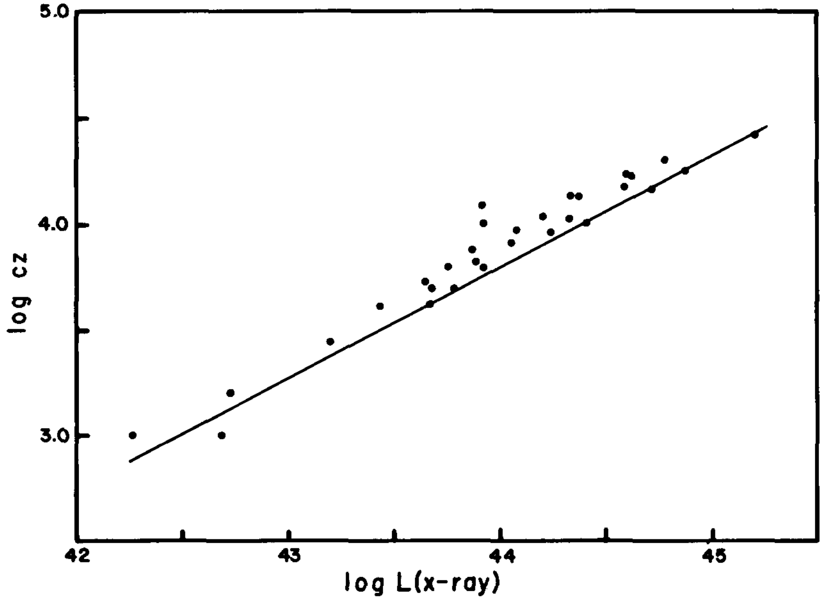

Figure 2: X-ray luminosity of Seyfert 1 (2-10 keV assuming $H_0 = 50$ km s^{-1} Mpc^{-1}) as function of redshift. Line defining envelope used to deduce luminosity function in table 3.

plot (Figure 2) shows a well-defined envelope for maximum luminosity as a function of distance surveyed. This means that the more luminous objects occur less frequently, so a larger volume of space has to be surveyed to find them. If all Seyfert 1 are part of a power-law luminosity function and are evenly distributed in space, the envelope is linear in a log-log plot. The volumes surveyed should be corrected for the fact that surveys for extragalactic objects are confused by the Milky Way. For this reason, I assume that the Seyferts found only represent 65% (2.6 π steradians) of the extragalactic sky. The space density for Seyfert 1 of a given luminosity L_o is then taken to be $(4\pi/3)(cz/50)^3(2.6/4)10^{-9}$ Gpc^{-3}, where L_o and cz are taken from the envelope in Figure 2.

The luminosity function that arises is given in Table 3, in units of number of objects Gpc^{-3} per magnitude interval of luminosity. It is a power-law luminosity function that increases by a factor of four for each magnitude decrease in luminosity. For comparison, the results of Tananbaum et al. (1978) are shown. Both functions are in good agreement at the lower luminosities where most galaxies are found. Mushotzky et al. (1979) use spectral and source count data to confirm the results of Tananbaum et al., concluding that the luminosity function of Elvis et al. (1978) was too low by a factor of two. Given the uncertainties, it is not likely that the space density of Seyfert 1 galaxies is known to better than a factor of two in any luminosity bin, but there are probably not many more than in Table 3. This means that the contribution of *local* Seyfert 1 galaxies to the "diffuse" X-ray background at any X-ray energy is no more than 20% (Mushotzky et al. 1979).

We might, however, expect strong increases in space density with redshift if Seyfert 1 galaxies are low luminosity quasars, because quasars do show such increases. Like the optical properties, the X-ray properties of Seyfert 1 galaxies and quasars are similar, overlapping in luminosity and differing systematically (so far) only in redshift. The HEAO A-2 group has begun to make progress in getting X-ray spectra of Seyfert 1 (Mushotzky et al.). They find that spectra above 5 keV can be fit by either flat power laws or high temperature bremsstrahlung spectra. Importantly, however, the X-ray spectra found in such galaxies are similar to that in 3C 273 (Worrall et al. 1979). This, together with the luminosity overlap and similar X-ray/Hβ ratios, enhances the assumption that Seyfert 1 and quasars can be tied together with a single luminosity function and obey the same density evolution law. Schnopper et al. (1978b), in particular, have emphasized that emission-line galaxies other than Seyfert 1 (such as those in Table 2) could also account for much of the X-ray background. These sources are at the 10^{43} ergs s^{-1} level, and only 10^5 such objects Gpc^{-3} would be needed to explain the background. This is a small fraction of optically discovered emission-line galaxies. It seems that there is no lack of objects to explain an X-ray background of faint, discrete sources rather than a truly diffuse background.

Another reason for presenting the luminosity function in Table 3

Table 2

Other Galactic Nuclei Showing X-rays and Strong Emission Lines

Galaxy	Position	Flux	L(x-ray)	cz	x-ray/Hβ	References
NGC 1097	0245-304			1270		10
NGC 1275	0318+414	18.9	44.38	5290		3
NGC 1365	0333-362	1.5	42.23	1570	1.6	5
NGC 1672	0445-593			1140		15
NGC 2110	0551-073	7.0	43.16	2130		2,16
NGC 2992	0945-142	6.9	43.18	2200	3.0	5,6
MCG 5-23-16	0945-300	7.7	43.34	2498		18
NGC 3227	1022+200	4.1	42.26	1000	1.8	2,3
NGC 5033	1312+367	3.6	42.18	960		2
NGC 5506	1412-031	6.6	43.00	1820	2.1	3
NGC 6221	1651-592	7.2	42.60	1250		2
NGC 7582	2317-425	3.6	42.55	1470	2.4	5
		mean =	42.88			

References and explanations same as for table 1.

Table 3

Seyfert 1 Luminosity Functions

log L(x-ray)	ϕ_1(x-ray)	ϕ_2(x-ray)	ϕ(Hβ)
42.4	6.1×10^4	4.2×10^4	-
42.8	1.5×10^4	1.3×10^4	-
43.2	3.4×10^3	3.9×10^3	29×10^3
43.6	8.4×10^2	1.2×10^3	4.8×10^3
44.0	1.8×10^2	3.6×10^2	7.4×10^2
44.4	46	108	120
44.8	11	32	21
45.2	2.5	-	3.5

Units of ϕ are number Gpc^{-3} per magnitude interval of luminosity. ϕ_1(x-ray) is derived in this paper using figure 1; ϕ_2(x-ray) is from Tananbaum et al. (1978); ϕ(Hβ) is from Sramek and Weedman (1978) and is scaled assuming L(x-ray)/L(Hβ) = 100.

is to compare it with one derived for Seyfert 1 by identical precepts, except using Hβ as the luminosity indicator (Sramek and Weedman 1978). We still need to know if *all* Seyfert 1 nuclei are X-ray sources at similar levels. (Remember that luminosity functions determined from X-ray or Hβ fluxes apply only to the *nuclei* of Seyfert 1 and might differ from results based on magnitudes of entire galaxies.) Comparing the results in Table 3 indicates that there are many more optical Seyferts at the low luminosity end, but comparable numbers at high luminosities. I am not yet sure this is a real difference because of the small numbers of galaxies that are used to determine the function at the low end. The consequence of such differences is that there should be a correlation in Figure 1 such that X-ray/Hβ increases with L(X-ray). A formal solution to the Seyfert 1 points gives the line shown in Figure 1, which is in the right direction.

Having postponed it as long as I can, it is now necessary to consider the assortment of leftovers in Table 2. The only consistent thing about these galaxies is that they are not clearly Seyfert 1. NGC 3227 is not classified consistently; I thought it looked like other Seyfert 2, but Elvis et al. 1978 detected broad wings so called it Seyfert 1. The definition of a Seyfert 2 is that all lines are broad; on order 10^3km s^{-1}, but of the *same* width, so that there are no differences between permitted and forbidden lines. It turns out that the forbidden lines are very strong relative to the Balmer lines in Seyfert 2. Several of the galaxies in Table 2 seem to come close to these criteria, especially NGC 3227, 2992 and 5506. Studying the X-ray properties of such objects should help a lot in deciding if Seyfert 1 and 2 depend only on variations in the gas distribution within fundamentally similar nuclei, as argued by Osterbrock (1979). Furthermore, there are NGC 1275 and NGC 2110 which could be called narrow-line radio galaxies, using Osterbrock's terminology, that are considered analogous to Seyfert 2. Other galaxies in the short list - NGC 1365, NGC 1672 and NGC 1097 - are thought to have emission lines similar to those from conventional HII regions. Now is not the time to try and make sense out of this assortment. HEAO-2 is observing large numbers of these lower luminosity galactic nuclei, so we should know soon whether there are large classes of X-ray galaxies other than the Seyfert 1.

Long after the HEAO telescopes have joined Skylab, their data will be a vital legacy in our pursuits of the infernal machines powering these nuclei. For an optical astronomer, the most pleasing result from X-ray astronomy is that the most energetic and exciting places in the universe are places that we can see, too. It would be very dismaying if most X-ray sources were empty fields! As it is, there is plenty for us all to do, regardless of our preference for frequency.

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