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X-RAY, OPTICAL, AND RADIO PROPERTIES OF QUASARS[1]

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ABSTRACT

We have examined a sample of 26 low-redshift quasars for relationships between X-ray luminosity and optical spectroscopic features. All quasars were observed with the *Einstein Observatory* and with the IDS on the Lick 3 meter telescope. We find evidence for correlations between quasar X-ray luminosity and both optical continuum luminosity and Hβ luminosity. In the latter case, there is a smooth relationship connecting quasars, Seyfert 1, and Seyfert 2 galaxies. For the quasars in this sample, there is also a strong correlation between optical continuum luminosity and both the Hβ luminosity and equivalent width. Unlike the case for Seyfert 1 nuclei, there is no evidence for a correlation between X-ray luminosity and either the Hβ/[O III] ratio or the width at zero intensity of the Hβ line. However, we do find some evidence for a weak correlation between α'_{ox}, the mean continuum spectral index between 5000 Å and 2 keV, and Fe II equivalent width, Hβ equivalent width, Hβ line width at zero intensity, and the ratio of Hβ equivalent width to its line width at zero intensity. Overall, we found few strong correlations between optical spectroscopic quantities and X-ray properties of quasars. Some of the implications of these results for models of quasars and quasar emission line regions are discussed.

Subject headings: galaxies: Seyfert — quasars — X-rays: sources

I. INTRODUCTION

The *Einstein Observatory* has provided the first opportunity for astronomers to investigate in a systematic fashion the radiation at X-ray frequencies from a large number of quasi-stellar objects (quasars). The X-ray luminosities of quasars are generally comparable to their optical and radio luminosities; therefore, a study of their X-ray properties may furnish additional insights into the physical nature of quasars. One obvious area of study involves comparing the characteristics of quasar radiation at optical and radio frequencies with those measured in X-rays. Tananbaum *et al.* (1979), as well as Ku, Helfand, and Lucy (1980) and Zamorani *et al.* (1981) have found that quasar X-ray luminosity correlates with both optical and radio luminosity. The relation between quasar X-ray properties and optical spectroscopic features has so far been largely unexplored, as has the relation between quasar X-ray properties and those of Seyfert nuclei.

We have at Lick Observatory a rather extensive set of data on the optical properties of quasars which have also been observed at X-ray frequencies. We have searched these data for correlations, both those suggested by theoretical considerations and those potentially interesting correlations not presently treated in theoretical investigations. This paper presents a compilation of the data we have available and our analysis of these data for correlations. The data on quasars are described in § II. In § III we discuss the correlation between X-ray properties and optical and radio properties of quasars. Some implications of our results for models of quasars and quasar emission line regions are discussed in § IV.

II. DATA AND MEASUREMENTS

To provide a sample of quasars for which the same spectral features are accessible, most of the 26 objects in this study have redshifts less than 0.4, the only exceptions being three objects with $0.4 < z < 0.58$ for which the optical data were already available. At a redshift of 0.4, Hβ falls within the atmospheric B-band. This sample includes all such low-redshift quasars known to have been observed from the *Einstein Observatory* and which are accessible from Lick Observatory. All quasars were observed with the image-dissector scanner (Robinson and Wampler 1972) on the remote-control spectrograph of the 3 m Shane reflector. A number of the more recent observations were obtained in the spectropolarimetric mode (Miller, Robinson, and Schmidt 1980). Resolutions of 8 or 16 Å were used, with total integration times ranging from 16 minutes to 14 hours. The best-observed objects were part of a program of spectrophotometric monitoring of optically variable quasars. These were each observed on several occasions, and the adopted

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TABLE 1

OPTICAL, X-RAY, AND RADIO PROPERTIES OF QUASARS

Name	Designation	z	$Log_{10}L_x$ (0.5-4.5 keV)	α'_{ox}	α_{ro}	$Log_{10}L_c$	α_{opt}, corr.	$L_{H\beta}/L_c$ Å	L[O III]/L_c Å	Fe II/H	HWZI of Hβ Å
PG 0026+129	0026+129	0.142	44.90	1.15	<-0.01	41.34±0.11	0.66±0.25	57±6	33.6±1.5	0.33±0.07	73±10
PHL 909	0054+14	0.171	44.75	1.24	<0.14	41.45±0.11	0.41±0.25	56±13	10.4±0.2	0.29±0.06	120±15
PHL 1027	0130+03	0.363	44.91	1.12	<0.26	41.25±0.11	0.03±0.25	103±9	25±5	<0.33	115±20
3C 47	0133+207	0.425	45.72	1.02	0.70	41.79±0.04	0.42±0.15	27±10	24.8±3	-	150±35
NAB 0137-010	0137-010	0.334	44.88	1.14	<0.21	41.28±0.11	-0.12±0.25	95±6	44±5	<0.15	92±12
PHL 1092	0137+06	0.396	44.30	1.48	<0.21	41.70±0.11	0.75±0.25	a	<3.6	-	a
PKS 0403-13	0403-13	0.571	45.40[b]	1.08	0.79	41.64±0.04	0.29±0.15	c	13.5±0.9	-	<81
PKS 0736+017	0736+017	0.191	44.44	1.19	0.58	40.99±0.04	0.13±0.25	25±5	<1.0[d]	0.71±0.14	81±9
3C 215	0903+16	0.411	45.15	0.89	0.65	40.84±0.04	e	69±16	116±8	0.17±0.03	68±15
4C 13.41	1004+130	0.240	<44.15	>1.62	0.43	41.96±0.04	0.06±0.20	25±6	8.9±1.0	0.34±0.07	125±20
1028+313	1028+313	0.177	44.94	0.59	0.48	39.75±0.11	0.42±0.20	185±25	91±10	0.25±0.05	83±18
PKS 1217+023	1217+023	0.240	45.41	0.87	0.50	41.04±0.04	0.92±0.12	122±12	72.6±2	0.26±0.05	73±14
TON 616(4C25.40)	1223+25	0.268	44.53	1.25	0.39	41.25±0.11	0.14±0.30	79±16	68±6	<0.20	115±15
3C 273	1226+02	0.158	46.23	0.86	0.60	41.82±0.11	0.06±0.15	71±10	<2.5[d]	0.50±0.10	116±13
3C 277.1	1250 56	0.321	44.35	1.21	0.70	40.95±0.11	0.33±0.25	95±15	158±20	<0.13	74±10
3C 279	1253-05	0.538	46.04	0.84	0.86	41.57±0.04	0.64±0.40	30±15	49±10	<0.50	69±25
PG 1351+64	1351+64	0.088	43.15±0.18[f]	1.73	0.22	41.27±0.04	0.28±0.10	45±15	43.1±1.5	<0.06	158±20
PKS 1510-089	1510-089	0.361	45.30	1.12	0.67	41.65±0.04	0.33±0.25	115±20	8.7±2	0.50±0.10	69±13
3C 323.1	1545+21	0.264	45.30	1.10	0.61	41.60±0.04	0.53±0.25	64±10	46.3±3	0.22±0.04	100±18
TON 256	1612+26	0.131	44.53	1.23	0.25	41.18±0.11	0.62±0.25	132±50	168±10	0.35±0.07	91±11
MC2 1635+119	1635+119	0.146	44.43	1.10	0.41	40.72±0.04	0.93±0.10	68±6	15.3±0.6	0.53±0.11	125±22
3C351	1704+60	0.371	44.97	1.37	0.50	42.06±0.04	-0.04±0.06	27±10	45±6	0.17±0.05	134±18
V 396 Her	1720+246	0.175	44.04±0.16[f]	1.30	<0.32	40.90±0.04	e	87±25	10.9±2	0.74±0.16	108±25
1803+676	1803+676	0.136	44.41	1.24	<0.5	41.10±0.11	0.19±0.25	101±15	37.5±4	0.20±0.04	127±15
PHL 1657	2135-147	0.200	45.23	0.97	0.51	41.15±0.04	0.53±0.12	150±25	142±9	<0.10	106±18
OX 169	2141+17	0.213	44.2±0.3[b]	1.22	0.44	40.84±0.11	0.34±0.15	64±10	14.9±1	0.26±0.05	90±9

a - Falls within atmospheric B-band.
b - There is evidence of X-ray variability.
c - Falls within atmospheric A-band.
d - [O.III] very weak or absent (See e.g. Baldwin 1975).
e - Wavelength range observed is too short for reliable determination of α.
f - Includes counting errors only.

spectral properties and fluxes are averages from the available data. The observed portion of the spectrum always included Hβ and, when present, [O III] λλ4959, 5007, and in some cases extended from Mg II λ2798 to Hα.

The absolute flux scale was established through observations of the Stone (1974, 1977) standard stars with an aperture (8″) large enough to substantially eliminate the effects of atmospheric dispersion. The quasars were observed through smaller apertures (usually 2″.4×4″) in the interest of spectral purity. Correction for scattered light and atmospheric dispersion in the quasar data was performed either using brief observations of the quasars through a large aperture (as was done in slightly more than half the cases) or, in the absence of such observations, by means of an empirical correction appropriate to average conditions at Mount Hamilton (French and Miller 1981).

Quantities measured from these spectra are listed in Table 1 along with identifying information and X-ray data for the 26 observed quasars. The optical properties included are those which could be reliably measured in most or all of the quasars in this sample. L_c is the continuum luminosity at 5000 Å in the emitted frame (in units of ergs s^{-1} Å^{-1}), computed using $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, and a galactic reddening law of the form used by de Vaucouleurs and Malik (1969) as revised by de Vaucouleurs, de Vaucouleurs, and Corwin (1976). L_c represents the contribution due to the featureless continuum only. The continuum was fitted by a power law over as much of the spectrum longward of the UV "bump" as available. The spectral index of the fit (in the sense $L_\nu \propto \nu^{-\alpha}$), after correction for galactic reddening following the treatment of Sandage (1966), is listed as $\alpha_{\text{opt,corr}}$. The luminosities in the Hβ and the [O III] lines (the 4959 and 5007 Å lines are summed) are tabulated as equivalent widths relative to the power-law continuum, since these are more precisely known than are the absolute luminosities. The larger errors in Hβ reflect uncertainties in defining the limits of the broad line wings. As an indicator of the strength of Fe II emission, the intensity of all Fe II lines between Hγ and Hβ is listed as a flux ratio to Hβ, measured after power-law subtraction and correction for He II λ4686 emission. Finally, the half-width at zero intensity (HWZI) of the blue wing of Hβ is listed, measured from the peak of the narrow core of the line if such a core is present. This represents our attempt to define the full extent of the line, and reflects the width beyond which no line contribution appears in our spectra. The blue side was chosen to avoid contamination by the [O III] lines.

Examples of the data obtained and our Hβ width estimates are shown in Figures 1 and 2. Figure 1 shows a portion of the spectrum of PKS 2135−147, which has a relatively simple, though composite, Hβ profile, rather similar to those encountered in Seyfert 1.5 galaxies. The HWZI measurement is relatively unambiguous in this case. The quasar 3C 47 (Fig. 2) presents difficulties representative of those encountered in several objects. The broad component of Hβ is so weak and wide that it is properly seen only after subtraction of the power-law continuum. In addition, the [O III] lines are clearly resolved, so that the red side of the broad Hβ profile is

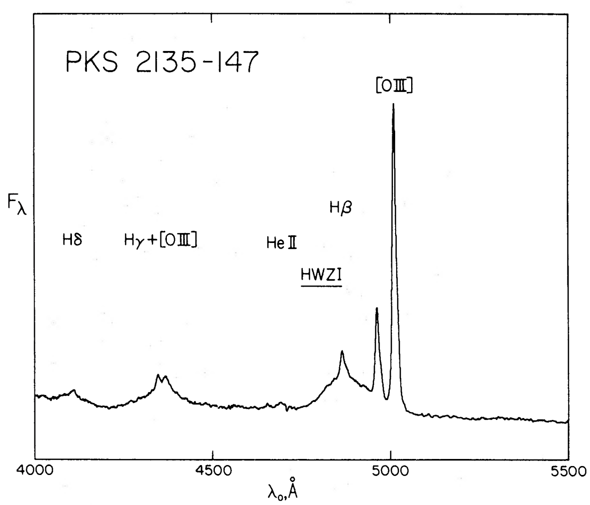

FIG. 1

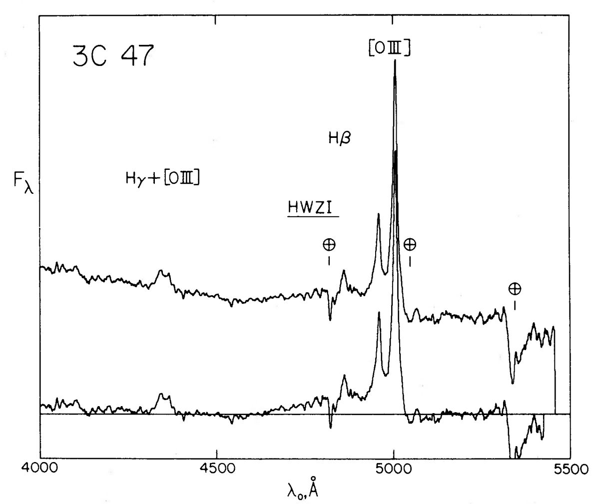

FIG. 2

FIG. 1.—A portion of the spectrum of PKS 2135−147 (PHL 1657). The assigned value of Hβ blue half-width at zero intensity (HWZI) is marked. Note the relatively sharp, narrow peak at Hβ. The zero flux level is at the bottom of the graph.

FIG. 2.—A portion of the spectrum of 3C 47. The upper spectrum is plotted as observed, while the lower one is shown after subtraction of the power law continuum, showing the very broad, low-level wings of Hβ. The HWZI is marked as before. Terrestrial absorption features are indicated. The horizontal line represents the zero flux level for both spectra.

not simple to interpret. The spectrum of 3C 351 is similar to that of 3C 47 in these respects. The low level and extreme width of the Hβ profile in these cases accounts for the large errors of the relevant measurements. In all cases, the difficulty of determining the precise level of the continuum provides the greatest contribution to the errors for the half widths at zero intensity.

X-ray luminosities were taken from Tananbaum *et al.* (1979) and from Ku, Helfand, and Lucy (1980) except for PKS 0403−132, which was observed in 1980 with the *Einstein* IPC as part of our program to monitor violently variable quasars. There is some weak evidence for X-ray variability in PKS 0403−132 in our data, while OX 169 is known to exhibit X-ray variability (Tananbaum *et al.* 1979). Errors in X-ray luminosity are primarily due to uncertainties in the X-ray spectrum and instrumental calibration (and are approximately $\pm 30\%$), except for those few objects in which counting statistics or observed X-ray variability provide a larger uncertainty for the X-ray luminosity. The radio-to-optical (α_{ro}) spectral indices (between 5 GHz and 2500 Å) are taken from the sources above (except for PKS 0403−132). Previous authors have used an optical-to-X-ray spectral index α_{ox} between 2500 Å and 2 keV. We have defined a new optical-to-X-ray index between 5000 Å and 2 keV in the quasar frame. This is listed in Table 1 as α'_{ox}, and should be a more homogeneous and directly meaningful parameter than α_{ox}, which was often determined from very rough photometry.

Many additional properties could be measured from our data, but because of different spectral characteristics, wavelength ranges observed, and data quality, most are measurable for too few quasars to search for optical-X-ray correlations. The analysis here is confined to the properties listed in Table 1, which are at least representative of the basic components inferred to exist in quasars: radio, optical, and X-ray continuum sources, broad-line region, and narrow-line region.

III. RESULTS

Perhaps the most striking result of this study is the absence of very strong correlations between optical spectroscopic quantities and X-ray luminosity. Although several quantities do show some correlation with X-ray luminosity, they generally correlate more strongly with optical continuum luminosity.

In analyzing these data for possible correlations, we have divided the quasar sample into radio-loud and radio-quiet quasars. Rather arbitrarily, we defined radio-quiet quasars by the requirement that either $\alpha_{ro} \leq 0.40$ or that only upper limits to α_{ro} be known. As a result, there are 10 radio-quiet quasars in this sample of 26.

In several instances we correlate luminosity against luminosity for different continuum or spectral luminosities. Such a procedure is not valid for a magnitude-limited sample, where flux should be correlated against flux. However, our quasar sample is not solely determined by a limiting flux, and in all cases the logarithmic range in luminosity spanned by the data is similar to the range in flux. Furthermore, we find no systematic change in the degree of correlation when fluxes rather than luminosities are correlated.

Throughout this section we shall discuss the probability that an uncorrelated sample would yield a certain correlation coefficient. It should be noted that when many correlations are searched for in a data sample, it is expected that a few will yield low probabilities even for uncorrelated data.

a) *X-Ray Correlations with Optical Continuum Luminosity*

Figure 3 shows the relation between the X-ray luminosity and the optical continuum luminosity at 5000 Å. As found by Ku, Helfand, and Lucy (1980) and Zamorani *et al.* (1981), there appears to be a correlation between X-ray luminosity and optical continuum luminosity. For the 25 quasars in this sample which have been detected at X-ray frequencies, the correlation coefficient is 0.36, which has a probability of 0.078 of occurring in an uncorrelated sample. This probability is significantly larger than that found by Ku, Helfand, and Lucy and by Zamorani *et al.* Such a result is to be

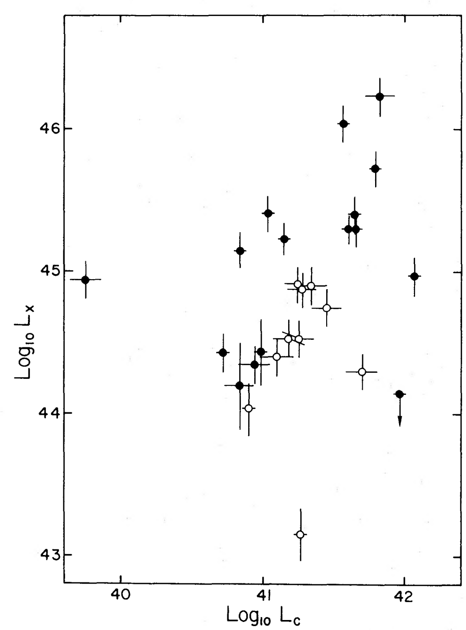

FIG. 3.—Logarithm of the 0.5–4.5 keV X-ray luminosity of quasars versus the logarithm of their continuum luminosity at 5000 Å. Open circles represent radio-quiet quasars, and filled circles represent radio-loud quasars. Radio-loud quasars are those with $\alpha_{ro} \geq 0.4$.

expected if cosmic scatter in the data is present, since both of their quasar samples were significantly larger than our sample of low redshift quasars. The scatter about a best fit line in these data is somewhat less for our quasar sample than for that of Zamorani *et al.* (1981), probably because they correlated X-ray luminosity with broad-band photometric magnitudes without correcting for the effect of emission lines. One would expect a better correlation with underlying optical continuum.

There are several other interesting features shown in Figure 3. As have been noted in previous studies, the X-ray luminosity of radio-loud quasars is usually higher than that of radio-quiet quasars for a given optical luminosity. In fact, for radio-loud quasars, the correlation between the X-ray luminosity and optical continuum luminosity shown in Figure 3 is even stronger than for radio-quiet quasars. The 15 radio-loud quasars have a correlation coefficient of 0.54, which has a probability of 0.034 of occurring in uncorrelated data.

In spite of these correlations, it is clear that the scatter of these data about a best fit curve is significantly larger than the observational uncertainties. It is noteworthy that the best fit to these data corresponds to a relation of the form $L_x \propto L_c^{1/2}$. This is consistent with the results of Ku, Helfand, and Lucy (1980), and it indicates that the X-ray luminosity increases slowly with increasing optical continuum luminosity.

Finally, there is a strong correlation between α_{ro} and α_{ox}, the spectral index between 2500 Å and 2 keV. For 17 quasars, the correlation coefficient between these two quantities is -0.6, which has a probability of 0.009 of occurring in uncorrelated samples. This inverse correlation is consistent with the result that radio quiet quasars are less luminous than radio-loud quasars at X-ray frequencies. We found no evidence that the spectral index of the optical continuum correlates with α'_{ox}, the spectral index between 5000 Å and 2 keV.

b) X-Ray Correlations with Emission Line Luminosities

Figure 4 shows the relation between the Hβ luminosity of quasars and their X-ray luminosity. Also shown in Figure 4 are data for Seyfert 1 and Seyfert 2 galaxies compiled by Kriss, Canizares, and Ricker (1980). It is clear that the quasars by themselves show a distinct correlation. For 23 quasars the correlation coefficient is 0.42, which corresponds to a probability of 0.045. It is striking from Figure 4 how well the relation between X-ray and Hβ luminosities for quasars joins the relation for Seyfert galaxies. In fact, the correlation coefficient for 50 quasars and Seyferts is 0.83, which has probability 8.8×10^{-16} of occurring in an uncorrelated sample. The slope of the best fit straight line is close to 2/3.

Figure 4 indicates that the relation between Hβ and X-ray luminosity for quasars is somewhat flatter than

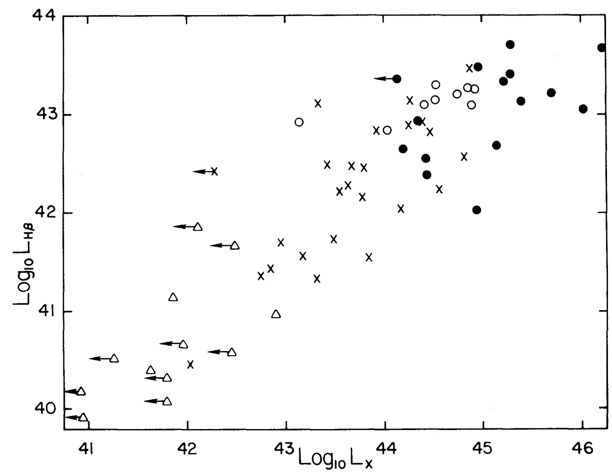

FIG. 4.—Logarithm of the luminosity in Hβ versus the logarithm of 0.5–4.5 keV X-ray luminosity. Filled circles represent radio-loud quasars, open circles represent radio-quiet quasars, crosses stand for Seyfert 1 galaxies, and open triangles represent Seyfert 2 galaxies.

that for Seyfert galaxies. It is also apparent that radio-quiet quasars have a larger Hβ luminosity than do radio-loud quasars for a given X-ray luminosity. If the Hβ luminosity is more strongly dependent on optical or UV continuum luminosity than on X-ray luminosity, one would expect this effect since radio-quiet quasars do have smaller X-ray luminosities. Indeed, there is no strong correlation between the Hβ equivalent widths of the quasars and their X-ray luminosities.

Figure 5 shows the Hβ luminosities for the quasars in this sample plotted against optical continuum luminosity at 5000 Å. There is clearly a very strong correlation, which corresponds to a correlation coefficient of 0.85 (probability $= 7 \times 10^{-9}$). Thus, the correlation between Hβ luminosity and X-ray luminosity of quasars may at least in part be due to the fact that Hβ correlates strongly with optical continuum luminosity, which in turn shows some correlation with X-ray luminosity. As always, the presence of a correlation between two variables does not necessarily imply a cause-and-effect relationship between them.

We have also plotted the Hβ equivalent widths for the quasars versus α'_{ox} in Figure 6. There is no significant correlation between these two quantities, although there is some evidence that sources with large α'_{ox}, i.e., sources with small X-ray luminosity compared to their optical continuum luminosity, have smaller Hβ equivalent widths. We also find that the Hβ equivalent width for quasars shows little correlation with X-ray luminosity.

In Figure 7 we plot [O III] luminosity versus X-ray luminosity for the quasars in our sample as well as for the Seyfert galaxies in Kriss, Canizares, and Ricker (1980). There is no evidence for a correlation between

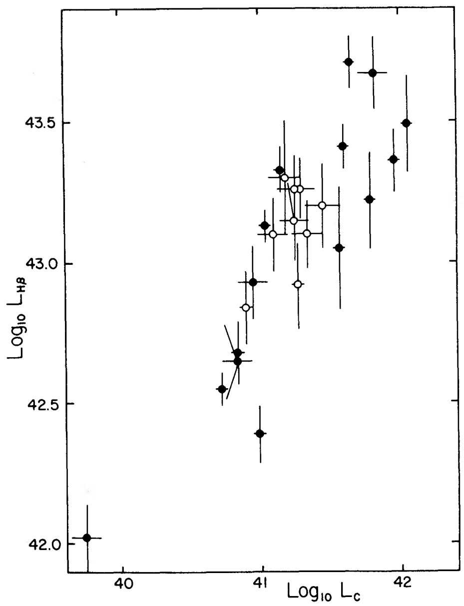

FIG. 5

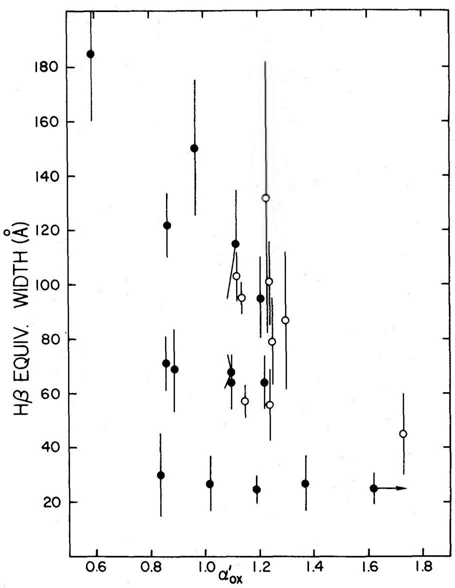

FIG. 6

FIG. 5.—Logarithm of the luminosity in Hβ versus the logarithm of the optical continuum luminosity at 5000 Å for quasars. Symbols are defined in Fig. 3.

FIG. 6.—The equivalent width of Hβ versus α'_{ox} for quasars. Symbols are defined in Fig. 3.

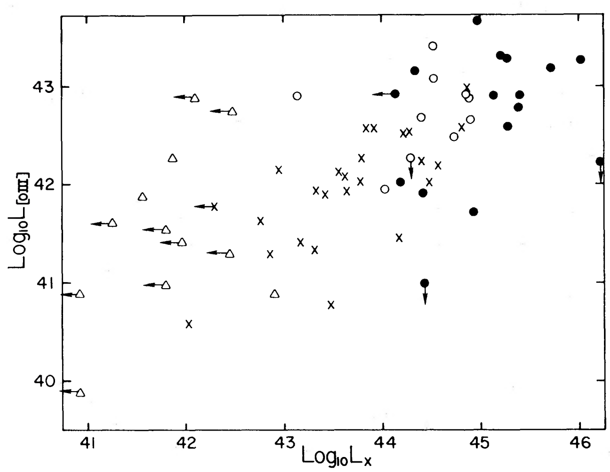

FIG. 7.—Logarithm of forbidden [O III] luminosity versus the logarithm of the 0.5–4.5 keV X-ray luminosity for quasars and Seyfert galaxies. Symbols are the same as in Fig. 4.

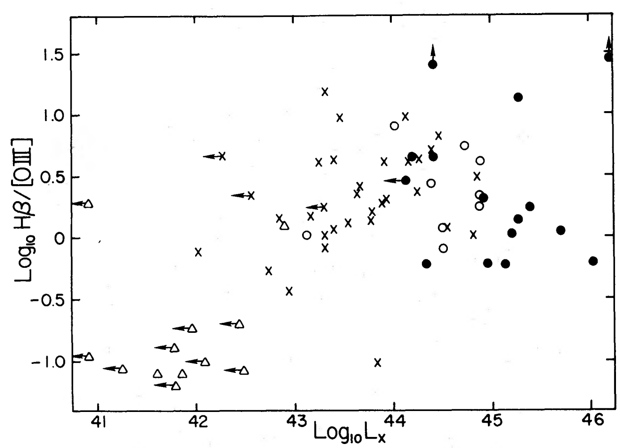

FIG. 8.—Logarithm of Hβ/[O III] versus the logarithm of the 0.5–4.5 keV X-ray luminosity of quasars and Seyfert galaxies. Symbols are the same as in Fig. 4.

X-ray luminosity and [O III] luminosity for the quasars or for the set of quasars plus Seyfert galaxies. There is also no evidence for a correlation between [O III] equivalent width and X-ray properties. We do, however, find evidence that the [O III] emission does correlate with optical continuum luminosity.

Grindlay *et al.* (1980) have demonstrated a correlation between the Hβ/[O III] ratio and the X-ray luminosity for radio-quiet Seyfert galaxies. Kriss, Canizares, and Ricker (1980) found that this correlation persists, although not as tightly, for their sample of Seyfert 1 and 2 galaxies. Their sample includes several radio loud Seyferts.

In Figure 8 we show the Hβ/[O III] ratio versus X-ray luminosity for our sample of quasars as well as for the data of Kriss, Canizares, and Ricker (1980) on Seyfert galaxies. It is clear that neither radio-loud nor radio-quiet quasars show any evidence for correlation. In addition, the apparently monotonically increasing relation between Hβ/[O III] and X-ray luminosity for

Seyferts does not persist to the higher X-ray luminosities of quasars. For radio-quiet quasars, the relation appears to turn over, while for radio-loud quasars, the scatter in the data is very high at large X-ray luminosity. This is due to the well-known absence of detectable [O III] emission in such quasars as PKS 0736 and 3C 273 (cf. Baldwin 1975).

We have also searched for correlations between Fe II emission and X-ray emission from quasars. Our sample contains no evidence for correlations between Fe II/Hβ and X-ray properties or between the equivalent width of Fe II and X-ray luminosity. However, for our set of quasars, there is some evidence for an inverse correlation between the Fe II equivalent widths and both α'_{ox} and the optical continuum luminosity. In the latter case, for 16 quasars the correlation coefficient is -0.47, which has a probability of 0.065 of occurring in an uncorrelated data sample.

c) X-Ray Correlations with Optical Line Profiles

Elvis *et al.* (1978), Kriss, Canizares, and Ricker (1980), and Elvis and Ward (1981) have all found strong evidence for a correlation between the full widths of the Balmer lines and the X-ray luminosities of Seyfert galaxies. In Figure 9 we show a log-log plot of the half-widths at zero intensity of Hβ versus X-ray luminosity for our sample of quasars as well as for the list of Seyferts given in Kriss, Canizares, and Ricker (1980). The line widths given in Kriss *et al.* are the full widths at zero intensity of Hβ. We have divided these full widths by a factor of 2 to obtain the half-widths at zero intensity. Since the Balmer line profiles of Seyfert 1 nuclei are sometimes asymmetric toward the red part of the profile, this procedure may, in some cases, slightly overestimate the half-widths on the blue side of the lines, which is the quantity measured for the quasars.

It is quite apparent from Figure 9 that the correlation seen in the Seyfert data is not present in our quasar sample. There is no evidence for a positive correlation between line width and X-ray luminosity for the quasars. If anything, there is slight evidence for an anticorrelation. For the data on the nine radio-quiet quasars shown in Figure 9, the correlation coefficient is -0.69, corresponding to a probability of 0.039. The data for the 14 radio-loud quasars shows no correlation at all. Even taking into account the slight overestimate of the Seyfert half width due to their Balmer line asymmetries, it appears that quasars do not extend the relation between line widths and X-ray luminosity seen in Seyfert galaxies.

In order to further investigate any possible relation between X-ray luminosity and line width, we measured the Hβ half-width at quarter-maximum (HWQM) for our sample of quasars. Before measuring the half-widths, we first subtracted from each line any narrow component having a profile similar to the corresponding forbidden oxygen line profile. Hence, these half-widths at quarter-maximum provide an additional measure of the line width arising solely within the broad permitted line region. We found some evidence for an anticorrelation between HWQM of Hβ and $\log L_x$ (correlation coefficient $= -0.39$ for 23 quasars), but neither the radio-quiet nor the radio-loud quasars alone showed any substantial correlation. It is therefore doubtful that the width of Hβ correlates with X-ray luminosity in quasars.

In Figure 10 we show the half-width at zero intensity of Hβ plotted against α'_{ox}. For these 23 quasars, there is some evidence for a positive correlation, with correlation coefficient $= 0.49$ (probability $= 0.017$). However, this correlation is mostly due to the few extreme points, and the radio-loud quasars alone show little evidence of correlation.

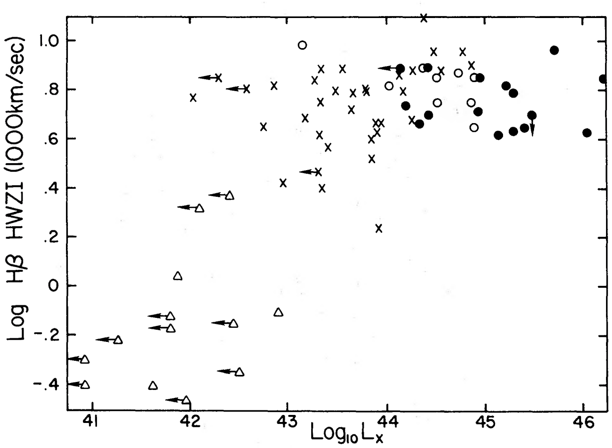

FIG. 9

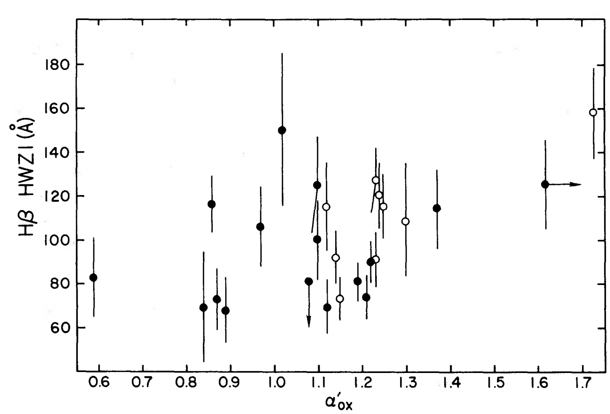

FIG. 10

FIG. 9.—Logarithm of the half-width at zero intensity of Hβ (in units of 1000 km s^{-1}) versus the logarithm of the 0.5–4.5 keV X-ray luminosity for quasars and Seyfert galaxies. Symbols are the same as in Fig. 4.

FIG. 10.—Half-width at zero intensity (in Å) on the blue side of Hβ versus α'_{ox}. Symbols are defined in Fig. 3.

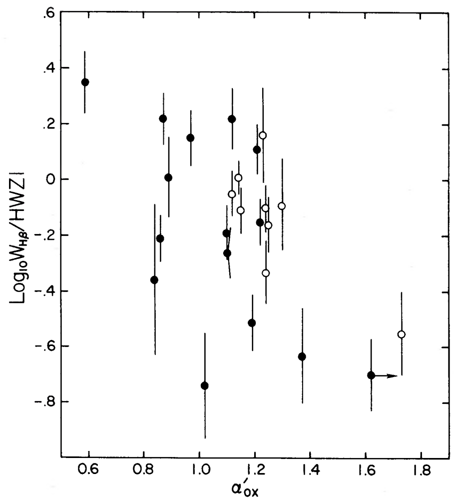

FIG. 11.—Logarithm of the ratio of Hβ equivalent width to Hβ half-width at zero intensity for quasars versus α'_{ox}. Symbols are the same as in Figure 3.

Finally, in Figure 11 we have plotted the ratio of the Hβ equivalent width to its half-width versus α'_{ox}. The ratio $W_{\mathrm{H}\beta}$/HWZI is a measure of how high the Hβ line rises above the continuum. There is evidence in Figure 11 for an anticorrelation between these quantities. For 23 quasars, the correlation coefficient is -0.44, which corresponds to a probability of 0.034. It is perhaps noteworthy that the most discordant point from the correlation in Figure 11 corresponds to 3C 279, for which the atmospheric A-band falls near the center of the Hβ profile.

IV. DISCUSSION

a) *Effects of Variability*

For the quasars in this sample, the X-ray observations and the optical spectroscopy were not done at the same time. Consequently, any X-ray or optical variability would lead to an artificially low significance for correlations between X-ray and optical properties. In fact, optically violently variable quasars, several of which are in our sample, are known to be among the most luminous quasars. However, X-ray variations in quasar emission are rarely observed. In addition, quasar emission lines are not observed to vary even when significant variations in the optical continuum luminosity are seen. We therefore expect variability to affect only the correlations involving either the optical continuum luminosity or the emission line equivalent widths of our quasars.

b) *Correlation between Optical and X-Ray Luminosity*

As has already been noted by Ku, Helfand, and Lucy (1980) as well as by Zamorani *et al.* (1981), the correlation between optical continuum luminosity and X-ray luminosity for quasars suggests an intimate relation between the two emitting regions. The fact that this correlation extends to the lower luminosity Seyfert galaxies implies that the central energy source in Seyfert 1 nuclei resembles the one in quasars.

The presence of a correlation between X-ray and optical continuum luminosity for radio-quiet quasars might be accounted for by emission from a very compact region. Such processes as emission from an accretion disk or nonthermal emission from a region which is very optically thick in the radio might account for this correlation. For radio-loud quasars, there must be an additional component of emission, for which the optical and X-ray emission correlate. This additional component could be associated with synchrotron–self-Compton emission (cf. Jones, O'Dell, and Stein 1974) or with asymmetric emission from a jet (cf. Blandford and Königl 1979).

c) *Relation between X-Ray Properties and Emission Line Strengths*

As stated earlier, the significance of the correlation shown in Figure 4 between Hβ and X-ray luminosity for quasars and Seyfert galaxies is not clear. On the one hand, this correlation is very strong, and the relations for quasars, Seyfert 1 galaxies, and Seyfert 2 galaxies connect smoothly together. On the other hand, for all three classes, the Hβ luminosity correlates much more strongly with the optical continuum luminosity, which in turn correlates with X-ray luminosity. The possible absence of a causal relationship between X-ray luminosity and Hβ luminosity is consistent with the fact that we found no significant correlation between Hβ equivalent width and X-ray luminosity for quasars.

It is now well known that for quasars and Seyfert nuclei the observed ratio of Lyα/Hβ is an order of magnitude less than that predicted by conventional case B recombination theory. Recently, it has been found that this discrepancy is avoided if Balmer emission from less highly ionized optically thick regions of quasar clouds are included in the calculations (cf. Mathews, Blumenthal, and Grandi 1980; Kwan and Krolik 1979, 1981). If this idea is correct, one would expect the broad Hβ emission from active galactic nuclei to depend on the relative amounts of ionization due to the UV and the X-ray continua. In particular, one would expect that for a given optical continuum luminosity, the Hβ emissivity should vary inversely with α_{ox}. The data in Figure 6 indicate a rather poor correlation between the Hβ equivalent width and α'_{ox} for quasars. There is an indication, however, that quasars with large α'_{ox}, i.e., with small X-ray luminosity relative to optical continuum luminosity, do have rather weak Hβ. Violently variable quasars have small α'_{ox}, and during periods of outburst they have smaller Hβ equivalent widths. The same is true of

BL Lac objects, which have very small Hβ equivalent widths and would populate the lower left portion of Figure 6.

The absence of a significant anticorrelation in Figure 6 could also be consistent with the optically thick cloud models if α'_{ox} is not a good measure of the relative strength of the UV continuum relative to the X-ray luminosity, or if either the emission line cloud environment (which determines the cloud density) or the covering factor varies from quasar to quasar.

In fact, the very strong correlation between Hβ emission and optical continuum emission for quasars as well as the correlation between Hβ and X-ray luminosity suggests that the covering factor must vary smoothly with luminosity along the sequence from Seyfert galaxies to luminous quasars. If the covering factor does not correlate with luminosity, it cannot vary greatly from object to object.

The very strong correlations between optical continuum luminosity and both Hβ luminosity and Hβ equivalent width are by far the best correlations found in our sample. The tightness to a straight line fit in Figure 5 suggests that the Hβ equivalent widths of X-ray loud quasars could be used as a distance indicator in a manner similar to that found by Baldwin (1977) for C IV in compact radio quasars. The difference is that Baldwin (1977) found $L_{\mathrm{C\,IV}} \propto L_c^{1/3}$, while the best straight-line fit to our quasar data yields $L_{\mathrm{H}\beta} \propto L_c^{2/3}$. Our data are consistent, however, with a linear straight-line fit ($L_{\mathrm{H}\beta} \propto L_c$), which was found by Yee (1980) and Shuder (1981) for the relation between $L_{\mathrm{H}\alpha}$ and L_c for a wide range of galactic nuclei. When the luminosity of a line is directly proportional to the continuum luminosity, the line equivalent width cannot be used as a distance indicator.

The absence of any correlation between forbidden oxygen emission and the X-ray properties of quasars (cf. Fig. 7) is consistent with models in which forbidden line emitting clouds are optically thin and located well outside the broad emission line region. The correlation between Hβ/[O III] and L_x seen by Kriss, Canizares, and Ricker (1980) suggests that the forbidden emission line region in Seyferts may be associated either with the active galactic nucleus or with the spiral galaxies in which most Seyferts are found. The fact that quasars do not extend this correlation is consistent with the latter view if the forbidden-line regions of Seyferts are ionization bounded while those of quasars are matter bounded, or if the galactic environments of quasars differ significantly from those of Seyferts.

Fe II emission is very similar to Hβ emission in that it is expected to arise from very optically thick low-ionization regions in quasar emission-line clouds. The only evidence we found for a correlation between Fe II emission and the X-ray properties of quasars is a slight anticorrelation between the equivalent width of Fe II and α'_{ox}. As is the case for the Hβ equivalent width discussed above, such an anticorrelation is expected if X-ray photons produce regions having low ionization in quasar clouds.

Steiner (1981) has recently proposed a spectroscopic classification scheme for active galactic nuclei and quasars based on the strength of the Fe II emission. He defined class A objects as those for which Fe II/H$\beta \geq$ 0.2. For these objects Steiner found a strong correlation between Hβ/[O III] and both the Hβ and X-ray luminosities. This led him to suggest that Hβ/[O III] might be used as a distance indicator for those active galactic nuclei and quasars having strong Fe II emission. The quasar data in Table 1 show no evidence for either of the two correlations found by Steiner. However, it should be noted that the range of luminosity spanned by the quasars in our sample is considerably smaller than the luminosity range in Steiner's (1981) plots. If one examines his diagrams over a limited range of luminosity, no correlation is observable. Indeed, the objects in Table 1 produce a scatter which is only slightly larger than the scatter about a best fit line in Steiner's (1981) figures. It should also be noted that the Fe II line strengths listed in Table 1 are integrated over a more limited range of wavelength than the Fe II line strengths used by Steiner (1981). We are therefore using a somewhat more stringent condition for the classification of a quasar as a strong iron line emitter.

d) X-Ray Correlations with Line Widths

It is noteworthy that the strong correlation between Hβ line width and X-ray luminosity found by Kriss, Canizares, and Ricker (1980) for Seyfert galaxies does not extend to the quasars in the sample considered here. Elvis and Ward (1981) have recently pointed out that this correlation for Seyferts is greatly improved when the 2–10 keV X-ray luminosity is used instead of the 0.5–4.5 keV luminosity. They attribute this to the fact that low photon energy X-ray absorption is present in Seyfert X-ray spectra due to a finite column density of gas along the line of sight. However, quasars are not yet known to show low energy X-ray absorption. Correcting the Seyfert 1 X-ray luminosities for absorption would tend to increase their 0.5–4.5 keV X-ray luminosity relative to the quasars in Figure 9. This would only slightly improve the correlation between line width and X-ray luminosity for the set of quasars plus Seyfert 1 galaxies (ignoring the Seyfert 2 galaxies), but it would significantly worsen the correlation between Hβ and X-ray luminosity shown in Figure 4.

One possible interpretation of the results in Figure 9 is that there is an effective upper limit to the velocity of broad emission line clouds in Seyferts and quasars. This upper limit may be associated with the structure of an accretion disk, with the effects of drag forces, or with the variation of cloud density with position in radiative acceleration models (Blumenthal and Mathews 1979).

Very optically thick clouds are less efficiently accelerated by radiation pressure than less thick clouds. One therefore expects that in such models the line widths should decrease with increasing cloud size, which in turn should increase with increasing X-ray luminosity relative to the UV continuum (Mathews 1982). Radiative acceleration of very optically thick clouds would therefore predict a positive correlation between line width and α_{ox}. There is some evidence for this in Figure 10. Since photoionization models predict that the equivalent width of Hβ should decrease with increasing α_{ox}, radiative acceleration requires an inverse correlation between $W_{\mathrm{H}\beta}$/HWZI and α_{ox}. Figure 11 provides some evidence for this. Models such as disk and infall models, in which the line widths are associated with cloud velocities produced by gravitation, predict no direct relationship between line width and α_{ox}.

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