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THE SOFT X-RAY PROPERTIES OF QUASARS

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ABSTRACT

We present first results of our *ROSAT* program to observe a complete sample of optically selected quasars. The sample selection criteria, combined with the PSPC capabilities, allow us to determine the soft ($\sim$ 0.2-2 keV) X-ray spectra of quasars with about an order of magnitude higher precision compared with earlier soft X-ray observations.

The complete sample includes 23 quasars, of which 10 were already analyzed. Most spectra are well characterized by a simple power-law, with $\langle \alpha_x \rangle = -1.50 \pm 0.40$. This average is significantly steeper than suggested by earlier soft X-ray observations of quasars. The 0.3 keV flux is well correlated with the 1.69 μm flux, which implies that the X-ray variability power spectrum of quasars flattens out between $f \sim 10^{-5}$ and $f \sim 10^{-8}$ Hz.

Strong correlations are also present between α_x and the following emission line parameters: Hβ FWHM, $L_{[\mathrm{O\ III}]}$, and Fe II/Hβ. These correlations suggest that: 1. The quasars' environment is optically thin down to $\sim$ 0.2 keV, 2. α_x is not significantly variable, 3. α_x might be a useful absolute luminosity indicator, and 4. The Galactic He I and H I column densities are well correlated.

Continuum-continuum correlations in our sample argue against either thin or thick accretion disks as the origin of the soft X-ray emission.

1. Introduction

The X-ray properties of quasars have been studied extensively over the last decade using *HEAO-1, EINSTEIN, EXOSAT*, and *GINGA* (e.g. Mushotzky 1984; Wilkes & Elvis 1987; Comastri *et al.* 1992; Lawson *et al.* 1992; Williams *et al.* 1992). These observations indicate that the X-ray emission above 1-2 keV is well described by a power law with a spectral slope $\alpha_x = d\ln f_\nu / d\ln \nu$ of about -0.5 for radio loud quasars and about -1.0 for radio quiet quasars.

X-ray observations below 1 keV indicate a spectral steepening, or equivalently an excess emission, relative to the flux predicted by an extrapolation of the hard X-ray power-law (e.g. Arnaud *et al.* 1985; Wilkes & Elvis 1987; Turner & Pounds 1989; Masnou *et al.* 1992; Comastri *et al.* 1992). In some objects the excess can be described as a very steep and soft component, which is consistent with the Wien tail of a hot thermal component dominating the UV emission. However, these studies were of limited quality because of the low signal to noise ratio (S/N) and low energy resolution of the *EINSTEIN* IPC, and the *EXOSAT* LE detectors, in particular in the crucial energy range below 0.5 keV. Furthermore, the objects studied do not form a complete sample, and these results are likely to be biased by various selection effects which were not well defined a priori. In particular, most studied objects are nearby, intrinsically X-ray bright, AGNs.

We use the PSPC detector to make an accurate determination of the soft X-ray properties of a well defined, complete, and otherwise well explored sample of quasars. This survey will allow us to address the following questions: 1. What are the soft X-ray spectral properties of normal, optically selected, low redshift quasars? 2. Are simple thin accretion disk models able to fit the observed optical/UV/soft X-ray continuum? are other modifying mechanisms, such as a hot corona required? are models invoking optically thin free-free emission possible? 3. Do the observed soft X-ray properties display any significant correlations with other properties of these quasars? Are these correlations compatible with various models for the continuum and line emission mechanisms?

2. The Sample

We found the BQS sample, a subset of the PG survey defined by Schmidt & Green (1983), to be particularly suitable for our purpose for the following reasons: 1. These objects are selected only by their optical properties, thus they are not biased in any direct way in terms of their X-ray properties. 2. This sample has already been studied extensively, and uniformly, in other parts of the spectrum. These studies provide us with the most complete and coherent picture of the emission properties of bright AGNs, and allow us to make a detailed study of possible correlations between the soft X-ray properties and various other emission properties. 3. This sample includes only bright quasars, thus high S/N spectra could be obtained within a reasonable amount of spacecraft time.

The complete PG sample includes 114 AGNs, of which 92 are quasars (i.e. $M_B < -23$). These objects were selected by a color criterion which according to Schmidt and Green is satisfied by $\sim$ 90% of all known quasars. We select a subsample of the PG quasars which is optimally suitable for soft X-ray observations. The following two selection criteria were used: 1. $z \leq 0.400$. This prevents the rest-frame 0.2 keV from being redshifted beyond the observable range. 2. $N_{\rm H\,I}^{\rm Gal} < 1.9 \times 10^{20}$ cm^{-2}, where $N_{\rm H\,I}^{\rm Gal}$ is the H I Galactic column density as measured in 21 cm. This low $N_{\rm H\,I}^{\rm Gal}$ cutoff is critical for minimizing the effects of Galactic absorption. This cutoff implies an upper limit on the Galactic optical depth in our sample of $\tau_{0.2\rm keV} < 1.6$. These criteria limit our sample to 23 quasars. The 10 quasars reported here are: PG 1114+445, PG 1115+407, PG 1216+069, PG 1226+023, PG 1309+355, PG 1322+659, PG 1352+183, PG 1415+451, PG 1512+370, PG 1543+489. These quasars were selected on the basis of their availability, and we do not expect a systematic bias in their intrinsic properties relative to the complete sample.

3. The Observations and Analysis of the Spectra

All the quasars were readily detected with a minimum of ~ 600 net counts, and typically ~ 2000, which allows an accurate determination of the spectral slope.

We fit each spectrum with a single power-law of the form $f_E = e^{-N_H \sigma_E} f_0 E^{\alpha_x}$, where σ_E is the absorption cross section per H atom, f_0 is the flux density at 1 keV, and E is in units of keV. We make three different fits for each object with: 1. N_H a free parameter, 2. N_H=$N_{\rm H\,I}^{\rm Gal}$. 3. N_H=$N_{\rm H\,I}^{\rm Gal}$, and $0.47 \leq E \leq 2.5$ keV. A comparison of these fits allows us to identify an intrinsic absorption or emission excess relative to a single power-law fit, to determine whether the 21 cm measurement of $N_{\rm H\,I}^{\rm Gal}$ is a reliable measure of the Galactic soft X-ray opacity, and to look for a dependence of α_x on energy.

In order to look for curvature in the spectrum we fitted a power-law model which includes an additional curvature term of the form $f_E = e^{-N_H \sigma_E} f_0 E^{\alpha(E)}$, where $\alpha(E) = \alpha_0 + \beta \log E$. These fittings were made using software developed by one of us (F.F.).

4. Results and Discussion

We find an average spectral index $\langle \alpha_x \rangle = -1.50 \pm 0.40$ for our 10 quasars, which is consistent with the RASS observations of AGNs analyzed by Walter & Fink (1993). The typical statistical error in α_x is only $2-4\%$, which is about an order of magnitude smaller than the typical error available for quasars in earlier observations. The *ROSAT* spectra of quasars clearly indicate that the soft X-ray slope is steeper than the hard X-ray slope. However, they suggest a steepening by $\Delta\alpha \sim 0.5$ below ~ 1 keV, rather than $\Delta\alpha \gtrsim 1$, and in some case a significantly larger steepening, below ~ 0.5 keV suggested by earlier X-ray observations (e.g. Turner & Pounds 1989; Masnou *et al.* 1992; Comastri *et al.* 1992).

The X-ray spectra of 9 of the 10 quasars described here (excluding PG 1114+445) are consistent with a single power-law shape at 0.15-2 keV. Deviations from a single power-law are typically 30% or less. Statistically significant deviations at a level of less than 30% are present in the spectra of 3C 273 and of PG 1512+370. PG 1114+445 is the only quasar where the deviations are significantly larger than 30%, and its spectrum is well described by a power-law + an absorption edge from highly ionized *O*.

The curved power-law model provides a significantly better fit in PG 1114+445 and 3C 273, but in both cases the new χ^2 is still high and more complicated models are suggested. None of the remaining 8 objects yielded a significant improvement of χ^2 at better than the 1% level. The best fit value for the curvature term β is within 2 σ of zero in these 8 objects.

We find a rather small scatter in the near IR to X-ray flux ratios. In particular, $f_{0.3\,\rm keV}$ in our sample can be predicted to within a factor of two, once $f_{1.69\,\mu m}$ is given. This result, together with the general lack of significant near IR variability in AGNs (Neugebauer *et al.* 1989), implies that the soft X-ray flux does not vary by typically more than a factor of two from the mean over timescales shorter than a few years. This indicates that the variability power spectrum in quasars does not continue to increase with increasing time scales, as observed at $f = 10^{-5} - 10^{-3}$ Hz, but flattens out somewhere between $f \sim 10^{-5}$ and $f \sim 10^{-8}$ Hz.

Both thin and thick accretion disk models predict the soft X-ray flux to be strongly dependent on inclination. These models therefore suggest a large range in the optical to soft X-ray flux ratio for accretion disks seen at a range of inclinations. These predictions contrast with the small range of optical to soft X-ray flux observed here.

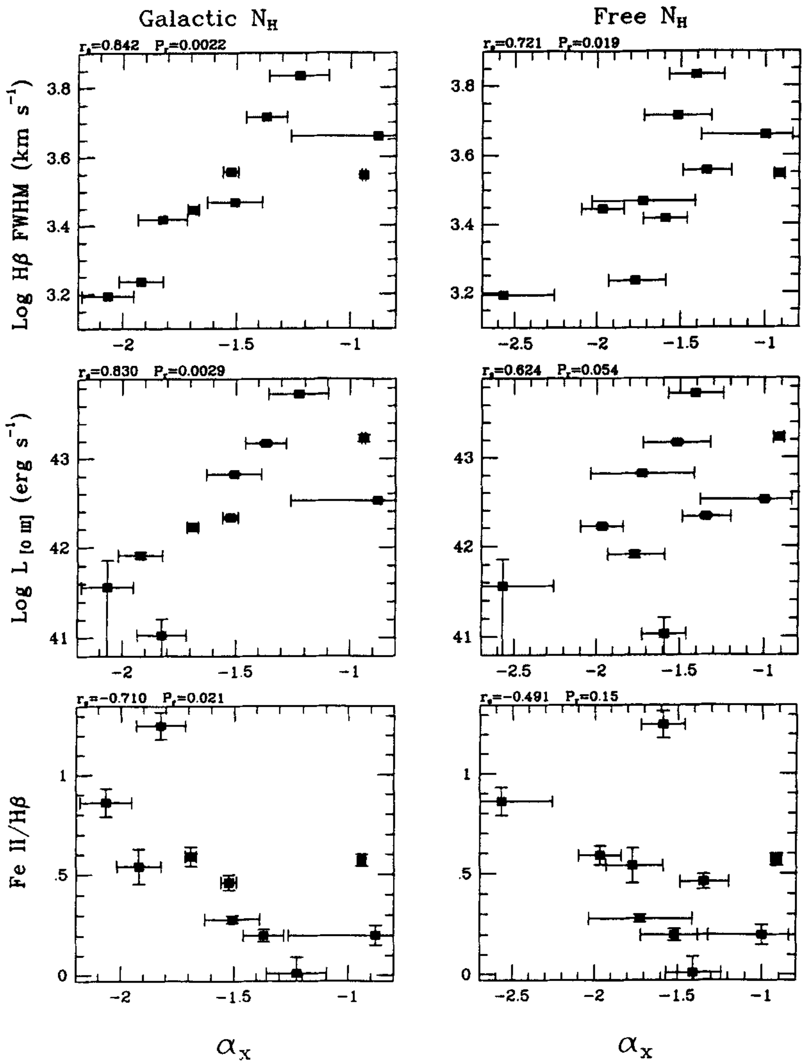

Figure 1. The emission properties which most strongly correlate with α_x. The Spearman rank-order correlation coefficients (r_S) and the significance levels (P_r) are indicated. Left panels, best fit α_x with $N_{\rm H}=N_{\rm H\,I}^{\rm Gal}$. Right panels, best fit α_x with $N_{\rm H}$ as a free parameter. All correlations with a fixed $N_{\rm H}$ are significantly stronger, which indicates that $N_{\rm H\,I}^{\rm Gal}$ is a good measure of the soft X-ray opacity. The strong correlation with $L_{[\rm O\ III]}$ indicates that α_x does not vary significantly in most object.

Remarkably strong correlation are suggested in our sample between α_x and the following emission line parameters: the FWHM of Hβ, the absolute luminosity of the narrow [O III] line $L_{[\mathrm{O\ III}]}$, and the Fe II/Hβ flux ratio (see Figure 1). These three emission line parameters are already known to be correlated with each other (Boroson & Green 1992). These correlations become significantly weaker when a free N_{H} rather than $N_{\mathrm{H}}{=}N_{\mathrm{H\ I}}^{\mathrm{Gal}}$ is used. This indicates that the H I column in the Galaxy, as measured in 21 cm, is a good indicator of the Galactic soft X-ray opacity. The typical $N_{\mathrm{H\ I}}^{\mathrm{Gal}}$ in our sample is $\sim 1.5 \times 10^{20}$ cm^{-2}, and at this column the Galaxy becomes optically thick only below $\sim$ 0.2 keV. The main opacity source at 0.2 keV is He I, which therefore implies that the H I column at high Galactic latitudes is very well correlated with the He I column. The presence of the strong correlations for $N_{\mathrm{H}}{=}N_{\mathrm{H\ I}}^{\mathrm{Gal}}$ also suggests the lack of a significant column of He I at the quasar's rest frame.

The strong correlation of α_x with $L_{[\mathrm{O\ III}]}$, together with the fact that $L_{[\mathrm{O\ III}]}$ is very unlikely to vary in quasars on time scales shorter than a few years, indicates that α_x also does not vary significantly, i.e. by more than $\sim$ 10% (as deduced from the scatter in Fig.1). This correlations connects the continuum shape of a quasar (α_x) with its absolute luminosity ($L_{[\mathrm{O\ III}]}$). This suggests that α_x might be a useful absolute luminosity indicator for quasars, which would allow quasars to be used as probes for the value of the cosmological density parameter Ω_0.

It is not clear what physical mechanisms are responsible for the strong correlations suggested here between α_x and the emission line parameters mentioned above. Further theoretical studies on the effects of the X-ray emission on the broad and narrow line emission might clarify the physical source of these correlations.

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