PERSISTENCE AND CHANGE IN THE SOFT X-RAY SPECTRUM OF THE QUASAR PG 1211+143

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ABSTRACT

Two *Einstein* and three *EXOSAT* observations of PG 1211+143 over a 6 year baseline show that strong steep-spectrum low-energy X-ray emission is a persistent feature of this quasar. *EXOSAT* observations of PG 1211+143 detected a factor of 2.3 increase in its steep soft X-ray (C-band) flux in 18 days. The bulk of the soft X-ray emission of PG 1211+143 therefore comes from a region less than 5×10^{16} cm across. In another (quasar rest frame) interval of 193 days the soft X-rays decreased by a factor of 3.7. Either an intrinsic emission variation or an increase of N_H from 3.4 to 7.6×10^{20} atoms cm^{-2} could produce the same change. In the same time interval the hard (2–10 keV) X-rays decreased by a factor 1.6 ± 0.05. This suggests a connection between the two energy regimes and argues against variable absorption causing the soft X-ray variations. In order to decrease in luminosity so rapidly a thermal source in PG 1211+143 would have to be optically thick to both electron scattering and free-bound absorption. The same argument applies to six of the seven other rapidly variable soft excesses reported in the literature, which suggests that optically thin thermal models are ruled out in general.

Subject headings: quasars — X-rays: sources — X-rays: spectra

1. INTRODUCTION

" Soft X-ray excesses" are a new component of the quasar continuum. At energies below the carbon edge at 0.28 keV (≥ 44 Å, the "C-band") half of all studied quasars and AGNs are dominated by large excess flux over an extrapolation of their higher energy power laws (Arnaud et al. 1985; Wilkes & Elvis 1987; Turner & Pounds 1989; Turner et al. 1990; Masnou et al. 1991; Comastri et al. 1991)[2]. It has been suggested that these soft X-ray/extreme-ultraviolet excesses are emitted from the inner edges of accretion disks (Arnaud et al. 1985; Bechtold et al. 1987; Czerny & Elvis 1987). In this case their radiation comes to us from the innermost identifiable region of a quasar. The spectral shapes of the soft X-ray excesses might then give us information on the peak temperatures in disks and hence determine the allowed values of the central masses and accretion rates.

Whatever their origin this new component deserves careful investigation. Existing constraints on their spectra are poor because the X-ray measurements cover a relatively small energy range (~ 0.1–0.3 keV) and have almost no energy resolution. Also very few objects were observed more than once so that variability information is scarce. Clearly more studies of these ultrasoft excesses are needed. Variability data in particular will be most important to distinguish between extended and compact emission regions, and to limit the properties of accretion disk models (Siemiginowska & Czerny 1989).

PG 1211+143 is an extreme case of a quasar with a soft X-ray excess. It has an excess extending to higher energies than in other cases (~ 2 keV; Bechtold et al. 1987), and is the only one of the 33 quasars with soft X-ray spectra in the *Einstein* IPC survey to be dominated by an extremely steep, soft X-ray spectrum (Wilkes & Elvis 1987). We therefore undertook a program of X-ray observations of PG 1211+143 with the *EXOSAT Observatory*. This paper reports this series of observations.

The value of the absorbing Galactic column density is crucial to studies of soft X-ray excesses (see, e.g., Elvis, Wilkes, & McDowell 1990). We use the accurate Galactic column density of $2.8 \pm 0.1 \times 10^{20}$ atoms cm^{-2} from the study by Elvis, Lockman, & Wilkes (1989). Values of the Hubble constant $H_0 = 50$ km s^{-1} Mpc^{-1} and of $q_0 = 0$ are used throughout. The redshift of PG 1211+143 is 0.085 (Schmidt & Green 1983).

2. OBSERVATIONS

PG 1211+143 was observed on three separate occasions by *EXOSAT* with intervals of 209 and 19 days between the observations. (For details of the *EXOSAT* instrumentation see de Korte et al. 1981 and Turner, Smith, & Zimmerman 1981). Table 1 gives details of the observations, including the derived count rates.

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[2] In fact their very soft spectra suggest that they would be more accurately named " XUV excesses" to denote the energy band below the carbon edge; however, common usage has settled on the less precise " soft X-ray excess" which could apply to any energy from ~ 0.2 to 2 keV.

TABLE 1

EINSTEIN AND *EXOSAT* OBSERVATIONS OF PG 1211+143

Year/Day	Instrument 'Filter	Exposure (s)	Count per second
1979/339	IPC	6306	0.89 ± 0.02
1980/347	IPC	1795	1.28 ± 0.03
1985/164	ME[a]	22370	0.84 ± 0.02
	LE/3LX	1257	0.206 ± 0.012
	LE/ALP	3539	0.0867 ± 0.006
	LE/BOR	16560	0.0087 ± 0.0012
1986/008	ME[a]	17030	0.52 ± 0.02
	LE/3LX	15753	0.055 ± 0.0025
1986/028	LE/3LX	10065	0.13 ± 0.004
	LE/ALP	15753	0.05 ± 0.009

[a] PHA 7–40, 2–10 keV.

The quasar was seen in all of the three energy bands defined by the "thin lexan" (3LX), "aluminum/parylene" (ALP) and "boron" (BOR) filters, which each cover the ~0.1–2 keV band with somewhat differently weighted responses, in front of the LE (low-energy channel multiplier array) during the first observation. In the later observations the source was fainter so the filters giving smaller effective areas (BOR, ALP) could not always be used. There were no serendipitous *EXOSAT* observations of PG 1211+143.

The positions of the source in all the LE detections are consistent with one another and with the optical (Schmidt & Green 1983) position of PG 1211+143 to within the 6″ uncertainties of the *EXOSAT* aspect (Osborne & Angelini 1986). The LE source appears pointlike in all the exposures. The mean LE position for the source is: $\alpha = 12^h11^m44^s.9 \pm 0^s.4$; $\delta = 14°19'53'' \pm 6''$ (1950.0).

The LE count rates (Table 1) were estimated using a square box centered on the source centroid and of a size which maximizes the signal-to noise ratio. The background was measured from a nearby source-free area of the image and rescaled to the source position to take into account spatial nonuniformities in the LE (Giommi 1985). The count rates were corrected for the fraction of counts outside the box (Davelaar & Giommi 1985), for vignetting effects, and for telemetry and instrumental dead times (Osborne 1985).

On the first two occasions the source was clearly detected in the ME (medium energy) argon detectors. Poor background subtraction in the third observation makes detection by the ME uncertain. The data from the "inner" detectors of the ME were much noisier than the "outer" detectors since they are less well shielded against particle background (Arnaud et al. 1985). We therefore used only the "outer" detectors in our analysis. Background subtraction for the ME was performed according to the method of Smith (1984). The background in each case was taken from the same detectors during times when they were pointed away from the source during an "array swap." Periods of high count rate due to solar flares were excluded by visually inspecting the light curves of each detector "half." The source is detected over the PHA range 7–40 which corresponds to 2–10 keV.

A serendipitous observation of PG 1211+143 (sequence number 6982) was made by the *Einstein* IPC (Imaging Proportional Counter, ~0.2–3.5 keV; Giacconi et al. 1979; Gorenstein, Harnden, & Fabricant 1981). This IPC observation was made in 1979, a year earlier than the targeted observation. This significantly extends our temporal baseline. In this observation the quasar was 21′.8 off-axis. At such positions the gain ("BAL," which measures the conversion from recorded pulse height to incoming photon energy) must be estimated using the spatial gain map ("DGNI"; Harnden et al. 1984). The "BAL" was 13.6 for this position (on a scale from ~12 to ~19). The IPC count rate has been corrected for vignetting and the loss of counts due to the degraded off-axis point response function. The targeted *Einstein* IPC observation of PG 1211+143, reported by Elvis, Wilkes, & Tananbaum (1985), Bechtold et al. (1987), and Wilkes & Elvis (1987), had a 20% higher count rate.

3. PERSISTENCE: A 6 YEAR SOFT EXCESS

The unusual feature of PG 1211+143 is its steep soft X-ray spectrum. It is important to understanding this emission to know whether it is persistent or transient. The five *EXOSAT* LE and *Einstein* observations allow us to test this.

We have fitted a simple power-law plus absorption model[3] to each of the data sets. Table 2 gives the results of these fits. (The spectrum from the first *EXOSAT* observation is reported by Comastri et al. 1991). The errors on each fit are quite large, but the error regions overlap in both spectral parameters. It is notable that the well-constrained fits (i.e., excluding the 79/339 and 86/008 data) give steeper values for the power-law index than are typical of either low-energy quasar spectra (Wilkes & Elvis 1987), or of higher energy AGN spectra (Mushotzky 1984; Turner & Pounds 1989). When the Galactic column density is imposed as a minimum value then slopes of around $\alpha_E \sim 2.0$ are required, even for the 79/339 (off-axis IPC) data. However, the χ^2 values even for the best fit values (Table 2) are not good, which suggests that the spectrum has curvature, steepening toward lower energies.

The LE data for 1985/164, having three data points, allow a fit to be made. This fit suggests an even steeper slope, ~3.0. A blackbody fit to the same 1985/164 LE data gives a best-fit temperature of 75 ± 5 eV.

The unusually steep spectrum of PG 1211+143 is thus not a transitory feature but is seen in observations spanning 6 years.

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[3] $f_v \propto v^{-\alpha_E}e^{-N_H\sigma}$, cross sections ($\sigma$) were taken from Morrison & McCammon (1983).

TABLE 2

Power-Law Fits to X-Ray Data for PG 1211+143

Year/Day	Instrument(s)	α_E[a]	N_H[a,b]	Norm[a,c]	χ^2, d.o.f.[d]	$P(\chi^2)$[e]
1979/339	IPC[f,g]	$1.3^{+0.9}_{-0.5}$	$0.9^{+1.5}_{-0.9}$	4^{+46}_{-1}	12, 5	0.04
1980/346	IPC[g]	$2.0^{+1.7}_{-0.6}$	$2.3^{+4.8}_{-0.6}$	$5.5^{+0.8}_{-0.7}$	12, 5	0.04
1985/164	ME[h]	$1.7^{+0.6}_{-0.4}$	0^{+85}_{-0}	$4.4^{+4.8}_{-1.3}$	48, 31	0.08
1985/164	ME[h] + LE	$1.8^{+0.3}_{-0.2}$	$2.2^{+1.5}_{-0.9}$	$4.8^{+1.3}_{-1.0}$	56, 34	0.01
1985/164	LE	$2.9^{+2.4}_{-0.9}$	$3.4^{+6.5}_{-1.5}$	$2.4^{+2.7}_{-2.1}$	0, 0	...
1986/008	ME[h]	$0.9^{+1.2}_{-0.6}$	$0.0^{+3.0}_{-0.0}$	$1.1^{+5.5}_{-0.6}$	47, 31	0.04
1986/008	ME[h] + LE	$0.9^{+0.7}_{-0.4}$	$0.3^{+2.5}_{-0.3}$	$1.1^{+1.3}_{-0.4}$	47, 32	0.04

[a] Ninety percent confidence ranges for three interesting parameters ($\chi^2_{min} + 6.25$; Avni 1976).
[b] 10^{20} atom cm^{-2}.
[c] Microjanskys at 1 keV.
[d] Degrees of freedom.
[e] Probability of obtaining the observed χ^2.
[f] PHA 2–9.
[g] Errors include IPC gain uncertainties at this off-axis position.
[h] PHA 7–40.

4. CHANGE: OPTICALLY THICK THERMAL EMISSION

On time scales of days to months significant variability is seen between each of the *EXOSAT* observations. In particular, in the quasar's frame, the LE 3LX data show a factor of 3.7 ± 0.3 decrease in 193 days and a factor 2.3 ± 0.1 increase in 18 days (Table 1). In the 193 day interval the hard (2–10 keV) X-rays also decreased, although only by a factor 1.6 ± 0.05. This may indicate some physical link between the emission in the two energy regimes.

The variations may be due either to intrinsic emission variability or to changing intervening absorption. At these low energies quite small column densities can produce such changes. To produce the decrease by a factor of 3.7 in the 3LX filter seen between the first (1985 June) and second (1986 January) *EXOSAT* observations needs an increase in N_H from 3.4×10^{20} atoms cm^{-2} (the best-fit value for the first observation) to 7.6×10^{20} atoms cm^{-2}. This is a minimum value. Material with a larger column density could obscure up to half the source to produce the same effect.

The contemporaneous decrease in the higher energy ME count rate by a factor of 1.6 argues against absorption as the only variable since 2–10 keV X-rays are negligibly affected by column densities less than 10^{21} atoms cm^{-2}.

If the XUV excess were due to an optically thin thermal plasma then its spectrum would be rich in diagnostic emission lines for the inner regions of quasars (Marshall 1991). However, the variability information rules out an optically thin plasma quite strongly, assuming an intrinsic change in the emission, since it requires large optical depths to both bound-free and electron scattering in the emitting plasma, as shown below.

If we take the decrease in 3LX count rate between the first and second *EXOSAT* observations to define a minimum cooling time, we can derive an optical depth for the emission region, taking into account electron scattering within the source, which smears out variations and increases the observed time scales by a factor $(1 + \tau_{es})$. Of course more rapid variations may have taken place between our observations, but the shorter implied cooling times only increase the required optical depth derived below. For simplicity we consider a uniform density sphere of constant temperature plasma.

A spherical optically thin source of radius r with electron density $n = \tau_{es}/r\sigma_{es}$ and temperature T has luminosity in the 0.1–0.3 keV range of

$$L = \frac{4}{3}\pi r^3 F_0\, fn^2 T^{1/2} B(T) = \left[\frac{4}{3}\pi\tau_{es}^2\sigma_{es}^{-2}F_0\, f\, T^{1/2}\exp\left(-\frac{0.1\ \text{keV}}{kT}\right)\right]r$$

where

$$F_0 = 2.4 \times 10^{-27}\ \text{ergs cm}^3\ \text{K}^{-1/2}\ \text{s}^{-1}\ ,$$

the bandpass factor

$$B(T) = \exp\left(-\frac{0.1\ \text{keV}}{kT}\right),$$

which is sensitive to the uncertain effective lower frequency limit of the soft excess observation, and f is a factor giving the additional contribution of recombination and line emission to bremsstrahlung cooling, $1 < f < 10$ (Raymond & Smith 1977; Raymond 1990). The radius in this equation can be related to the time scale set by the variability, t_{var} by

$$r \leq \frac{ct_{var}}{(1 + \tau_{es})}$$

(optically thick sources vary slowly for their size, so the inferred size is smaller for high depth), and so, combining the above equations,

$$\frac{\tau_{es}^2}{1 + \tau_{es}} \geq g$$

where

$$g = \frac{3L\sigma_T^2}{4\pi c t_{var} F_0 f T^{1/2} B(T)} = 1.4 \times 10^{-33}\left(\frac{L}{1 \text{ ergs s}^{-1}}\right)f^{-1}\left(\frac{t_{var}}{1 \text{ s}}\right)^{-1}(T/1 \text{ K})^{-1/2}\exp\left[-1.2\left(\frac{T}{1 \text{ K}}\right)^{-1}\right]$$

$$= 7.1 \times 10^2\left(\frac{L}{10^{44} \text{ ergs s}^{-1}}\right)f^{-1}\left(\frac{t_{var}}{1 \text{ day}}\right)^{-1}\left(\frac{T}{5 \times 10^6 \text{ K}}\right)^{-1/2}\exp\left[-0.24\left(\frac{T}{5 \times 10^6 \text{ K}}\right)^{-1}\right].$$

If $g < 1$, it is the square of the electron scattering depth. If $g > 1$, the assumption of optical thinness leads to a contradiction, and we may deduce that the source must be optically thick; g is then equal to the electron scattering depth as long as the formula for L remains valid.

Even if the source is optically thick to electron scattering, it will retain its optically thin spectral shape unless absorptive opacity is also present. Bound-free interactions are dominant in modifying the spectrum toward a blackbody. The bound-free optical depth τ_{bf} is just $\tau_{es}(\sigma_{bf}/\sigma_{es})$ (where the σ are the corresponding cross sections). The bound-free cross section at these subkilovolt energies depends only weakly on temperature in the range above 10^6 K; σ_{bf}/σ_{es} at 0.1–0.2 keV is in the range 1–5 with T between 10^6 and 10^7 K (Krolik & Kallman 1984; Kallman private communication) and so the spectrum will indeed be modified toward thermal form if the source is optically thick. The upper limit to the optical depth obtainable from comparing the blackbody radius to the variability time scale is not interesting.

The decrease in 3LX count rate between the first and second $EXOSAT$ observations of PG 1211+143 gives a value g of ~ 14 ($f = 1$), which implies that it is optically thick. If instead the flux decrease is due to changing absorption in front of the source then electron scattering delays do not apply. The variability gives the physical size directly if we assume an absorber local to the quasar which moves to occult at least the fraction of the source whose luminosity disappears. For a transverse velocity of the absorber, v, the optical depth to electron scattering is then $\sim 180(v/c)^{-1/2}$, which is considerable even for a relativistically moving intervening absorber.

Variability of soft X-ray excesses is now known to be common in quasars and AGNs (see summary in Elvis, Wilkes, & McDowell 1991). In some cases the variations are far more rapid than in PG 1211+143 (e.g., Mrk 335; Turner & Pounds 1988; Lee & Balick 1988). Table 3 lists the seven cases in the literature for which luminosities and time scales for luminosity decreases are given. (Only decreases in luminosity were used since only these define cooling times.) These variations imply the values of g listed in Table 3 and are shown in Figure 1 against lines showing the $g = 0.5$ ($\tau = 1$) and $g = 10$ loci for electron scattering.

PG 1211+143 is seen from Figure 1 (and Table 3) to be one of the least extreme of these soft X-ray excesses. Most are factors of 10–100 times more optically thick, to the extent that large values of g imply a large optical depth. (E1615+061 is the only exception but here the excess may not be real; Buckley et al. 1987). We conclude that optically thin emission rarely dominates the production of quasar soft X-ray excesses, so that the line emission will be broadened into a continuum. Optically thick emission would tend to support an origin in the central regions of an accretion disk, although we note that the physics of the inner edge are not well understood (Shakura & Sunyaev 1973), and that other processes (e.g., Comptonization; Czerny & Elvis 1987) could well modify the emitted disk spectrum.

The changes in the LE/3LX flux of PG 1211+143 between the $EXOSAT$ observations trivially rule out a source for the soft excess X-rays in extended regions on the scale of the optical/ultraviolet narrow emission line cloud zones (~ 100 pc–1 kpc), such as suggested by Halpern & Filippenko (1984) and observed in several Seyfert galaxies (Elvis et al. 1991). They would also have ruled

TABLE 3

Optical Depths for Variable Soft Excesses in AGN

Name	log L_{xs}[a] (ergs s^{-1})	log Δt (s)	Variability factor	g[b]	Reference
Mrk 335	43.6	4.3	2.0	1000	1, 2
Fairall 9	44.9	5.7	1.9	450	3
M81	40.5	2.7	2.0	30	4
3C273	45.2	7.2	1.7	65	5, 6
NGC 4051[c]	41.5	3.0	2.0	300	7
PG 1211+143	44.7	7.2	3.7	14	8
NGC 5548	44.6	4.4	1.3	8100	9
Mrk 841	44.4	4.6	1.5	3200	10
E1615+061[d]	44.0	8.0	1.5	0.5	11

[a] Luminosity in the soft excess, ~ 0.1–0.3 keV.

[b] For $T = 5 \times 10^6$ K, $f = 1$. Values are ~ 5 times smaller for $T = 1 \times 10^6$ K, while τ_{bf} is ~ 85 times larger.

[c] Note the warnings of Lawrence et al. (1987) about picking time scales from 1/f variations.

[d] But see Buckley et al. (1987) who note a nearby X-ray bright RSCVn system. This may be the cause of the apparent soft excess in this AGN.

REFERENCE.—(1) Turner & Pounds 1988; (2) Lee et al. 1988; (3) Morini et al. 1986; (4) Barr et al. 1985 (quoted in Barr & Mushotzky 1986); (5) Turner et al. 1990; (6) Masnou et al. 1991; (7) Lawrence et al. 1985; (8) this paper; (9) Kaastra & Barr 1989; (10) Arnaud et al. 1985; (11) Pravdo et al. 1981.
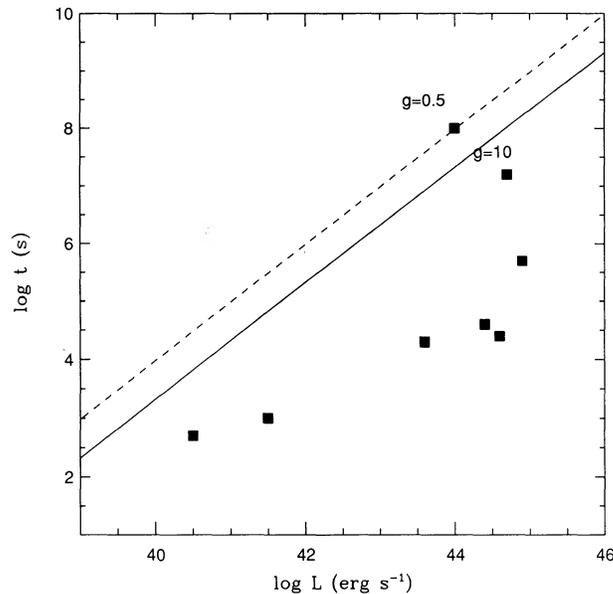
FIG. 1.—Luminosity in the "soft X-ray excess" component vs. observed time scale for a decrease in the soft X-ray component for the AGN from Table 3. The lines show values of $g = 1$ (marginally optically thick) and $g = 10$ for thermal emission with electron scattering. Larger optical depths lie to the bottom right, which implies that most soft excesses are optically thick.

out emission from the broad emission-line regions (Krolik, McKee, & Tarter 1981) under earlier assumptions about their size, however, recent observations (Peterson et al. 1990) suggest that sizes of 5–30 light days are quite plausible for these regions, comparable to the light travel time size limits derived for the soft excess emission regions.

5. CONCLUSIONS

Over five observations covering 6 years the steep low-energy X-ray spectrum of PG 1211+143 was always present. In this quasar the "soft excess" is a persistent feature.

EXOSAT observations of the quasar PG 1211+143 have detected large amplitude (factor > 2) short time-scale changes in its low-energy X-ray emission: an increase in 18 days and a decrease in 193 days. The small size implied for the bulk of the soft X-ray emission from PG 1211+143 implies large optical depths in the emitting plasma. This conclusion is true of most known variable soft X-ray excesses in AGNs and quasars. Optically thick emission is likely from the inner regions of an accretion disk, although modifications (due to, e.g., Comptonization) can occur, and the detailed physics is not well understood.

Observations of variability and spectra of the soft X-ray excess component of AGN continuum emission are proving valuable. *ROSAT* observations are likely to extend this work substantially.

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