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X-Ray Continuum with an Iron Emission Line from the Radio-Quiet Quasar PHL 909

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ABSTRACT. Results of the spectral analysis of the X-ray (0.1–10 keV) spectrum of the radio-quiet quasar, PHL 909, are presented. A spectrum of this quasar, which was observed on 1984/349, was obtained from the *EXOSAT* archives. Different models were used to fit the ME and LE+ME data. Fit parameters to the ME data show a steep spectral index for this quasar, typical of radio-quiet quasars. A weak "soft excess" was detected in PHL 909. Two-power-law and broken-power-law models fitted well with the LE+ME data. A highly significant ($>99.9\%$) emission line was detected with line center energy being in the range 5.9–6.6 keV and the measured equivalent width between 300 and 1000 eV. A thermal bremsstrahlung model with a Gaussian line component also fits well with the data set ($kT\sim 1.6^{+0.4}_{-0.3}$ keV), suggesting a cluster origin from the known cluster around this quasar. Alternatively the detected line emission may be due to the fluorescence of cold matter around the central continuum source outside our line of sight.

1. INTRODUCTION

PHL 909 [0054+144, $z=0.171$, $V=15.71$, $M_v=-24.3$ (Hewitt and Burbidge 1987)] is an unusual and interesting quasar since the optical-ultraviolet continuum "big bump" feature of this quasar appears to be weak, relative to both infrared and X ray. It is the weakest bump quasar among all the quasars studied by McDowell et al. (1989).

An X-ray observations of PHL 909 was carried out using the *Einstein* satellite (Zamorani et al. 1981; Wilkes and Elvis 1987; Masnou et al. 1991). This observation showed a flat X-ray spectrum ($\Gamma=1.3^{+0.4}_{-0.3}$) with a weak soft excess. No other X-ray spectral information is available for this quasar in the literature. For this reason we searched the *EXOSAT* archives and found that this quasar was observed once with *EXOSAT*. In this paper we present the detailed results of the spectral analysis of the *EXOSAT* low (0.1–2 keV) and medium energy (2–10 keV) spectra of PHL 909.

2. OBSERVATIONS

Low-energy (LE) data of PHL 909 were obtained by using Lexan 3000 (LX3) and aluminum/parylene (Al/P) filters [de Korte et al. (1981) have described the LE detectors in detail]. Medium energy (ME) spectra of this quasar were collected from eight argon-filled proportional counters or detectors [for detailed information on *EXOSAT* instrumentation and ME detectors, see White and Peacock (1988) and Turner et al. (1981), respectively], which were divided into two halves (the detectors numbered 1–4 are collectively known as half 1 and 5–8 together are known as half 2). These two halves can be either aligned to the pointing axis or offset by up to 2° to obtain background emissions. Background-subtracted LE and ME spectra of PHL 909 were obtained from the *EXOSAT* data base.

3. SPECTRUM ANALYSIS AND RESULTS

3.1 Power-Law Fits

The XSPEC (X-ray spectral fitting) software package was used to analyze ME and LE+ME spectra of PHL 909. A power-law model with absorption (model 1) [using the cross sections given by Morrison and McCammon (1983)] was used to fit the ME spectrum and the best-fit parameters with 90% confidence error bars which were computed for a given parameter, keeping the rest of the parameters free, are presented in Table 1. The 90% confidence limits on each parameter were computed by the procedure given by Lampton et al. (1976) ($\chi^2_{\rm min}+4.61$ for two free parameters). The value of the spectral index ($\Gamma=1.12\pm0.47$) is compatible with that of Wilkes and Elvis (1987). Fit parameters of model 1 (see Table 1) show that the value of the hydrogen column density ($N_{\rm H}$) is zero, which is unphysical because the minimum value of $N_{\rm H}$ should be the galactic column density value [4.2×10^{20} cm^{-1} (Elvis et al. 1989)]. Negative $N'_{\rm H}$ values imply a source spectrum with more emission than the power-law prediction at low energies, i.e., a "soft excess" (Wilkes and Elvis 1987; Kruper et al. 1990).

Results of the best-fit parameters of the power law +fixed absorption (fixed with the galactic $N_{\rm H}$ value) model are presented in Table 1 (model 2) and the χ^2 statistics suggest that this fit is also acceptable. The hard spectral index (obtained from the fits to the ME data only) of this quasar is flat. $\Gamma=1.13\pm0.47$. Figure 1 shows the ME spectrum of PHL 909 with the best-fit power law+fixed absorption model convolved through the detector response and the lower panel shows the residuals between the spectrum and the model.

A power law+absorption model (model 4) was used to fit the LE+ME spectra and the results are given in Table 2 (see model 4) which show that the galactic $N_{\rm H}$ value is zero. Thus we used this model with fixed $N_{\rm H}$ and the fit parameters are presented in Table 2 (see model 5). It can be seen from the χ^2_r value that model 5 also provides good fits to the LE+ME data. The spectral index of this quasar, obtained from the fits of model 5, is steep, $\Gamma=2.1\pm0.12$. From the comparison of the values of Γ, it is seen that the spectral index value obtained from the ME data fits is much flatter ($\Gamma=1.13\pm0.47$) than that obtained from the LE+ME data ($\Gamma=2.1\pm0.12$). This may be due to fixing the absorbing column density at the observed radio galactic value. It can be seen from the contour plots in Wilkes and Elvis (1987) that forcing a column density in the presence

TABLE 1
Spectral Fits to the ME Data

Model 1: Power Law+Absorption					
Γ[a]	N[b]	N_H[c]	χ^2_r/d.o.f.		
$1.12^{+0.47}_{-0.47}$	$0.51^{+0.49}_{-0.26}$	0<0.92	0.68/25		
Model 2: Power Law+Fixed Absorption[d]					
Γ[a]	N[b]	χ^2_r/d.o.f.			
$1.13^{+0.47}_{-0.47}$	$0.52^{+0.46}_{-0.26}$	0.70/26			
Model 3: Power Law+Fixed Absorption[d]+Gaussian Line					
Γ[a]	N[b]	E_L[e]	E_N[f]	EW[g]	χ^2_r/d.o.f.
$1.71^{+0.68}_{-0.64}$	$0.99^{+1.11}_{-0.56}$	$6.21^{+0.53}_{-0.41}$	$0.96^{+0.63}_{-0.66}$	510±340	0.48/24

[a] Photon index.
[b] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV.
[c] Column density in 10^{20} cm^{-2}.
[d] Fixed with the galactic N_H value (4.20×10^{20} cm^{-2}).
[e] Line energy in keV.
[f] Line intensity in 10^{-4} photons cm^{-2} s^{-1}.
[g] Equivalent width in keV.

of a soft excess always steepens the spectral slope. In such situation, it is better to make a two-component fit, as was done for this quasar in Masnou et al. (1991).

A power law+fixed absorption+Gaussian line (presence of Gaussian line feature will be discussed below) model was used to fit the ME data and the fit parameters are presented in Table 1 (see model 3). The ME spectrum fitted with this model is shown in Fig. 2 along with the residuals. Results of the fit parameters of model 3 show that this quasar displays a "canonical" spectral index value ($\Gamma=1.71^{+0.68}_{-0.64}$) in the 2–10 keV band and almost the same

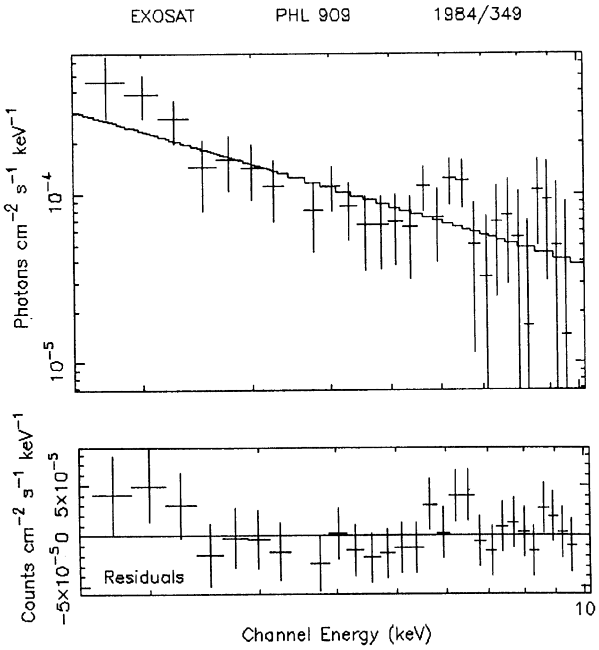

FIG. 1—Incident ME spectrum of PHL 909 fitted with a simple power law and fixed absorption model. The lower panel of the figure shows the residuals between the spectrum and the model in units of counts cm^{-2} s^{-1} keV^{-1}.

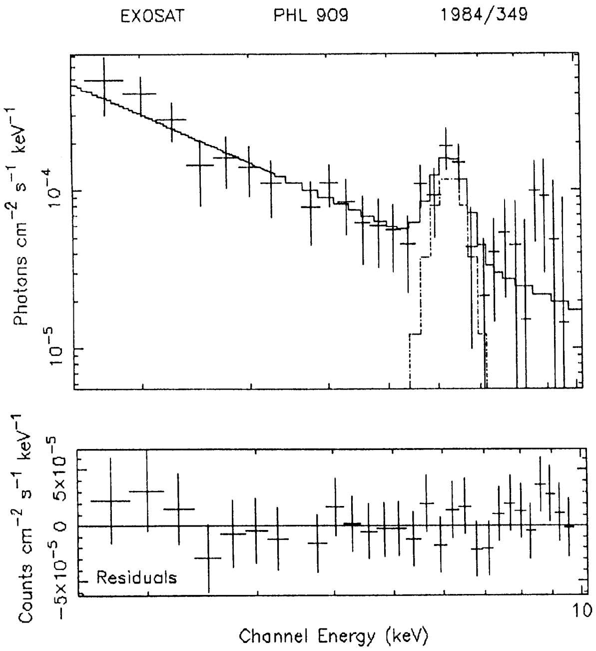

FIG. 2—Incident ME spectrum of PHL 909 fitted with a power law, fixed absorption, and a Gaussian line model. The residuals between the spectrum and the model are shown in the lower panel.

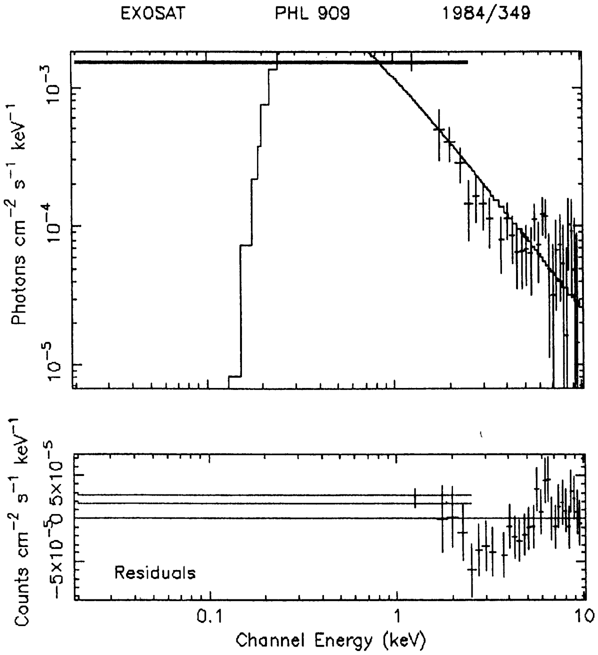

FIG. 3—LE+ME incident spectrum of PHL 909 fitted with a fixed power law ($\Gamma=1.7$) and fixed absorption model convolved through the detector response. Residuals are shown in the lower panel of this figure. Note the presence of a "soft excess" below 2 keV and an emission feature around 6 keV.

TABLE 2
Spectral Fits to the LE+ME Data

Model 4: Power Law+Absorption

Γ^{a}	N^{b}	N_{H}^{c}	χ_r^2/d.o.f.
$1.24^{+0.07}_{-0.07}$	$0.61^{+0.06}_{-0.07}$	0.0	0.84/27

Model 5: Power Law+Fixed Absorption[d]

Γ^{a}	N^{b}	Flux[e] 0.1–2 (keV)	Flux[e] 2–10 (keV)	L_X^{f} 0.1–2 (keV)	L_X^{f} 2–10 (keV)	χ_r^2/d.o.f.
$2.10^{+0.11}_{-0.12}$	$1.79^{+0.20}_{-0.19}$	4.51±0.55	3.95±0.34	6.68±0.81	5.85±0.50	1.04/28

Model 6: Fixed Power Law+Fixed Absorption[d]

Γ^{a}	N^{b}	χ_r^2/d.o.f.
1.70[g]	$1.31^{+0.14}_{-0.14}$	1.86/29

Model 7: Power Law+Power Law+Fixed Absorption[d]

Γ_1^{a}	N_1^{b}	Γ_2^{a}	N_2^{b}	χ_r^2/d.o.f.
1.7[g]	$1.06^{+0.18}_{-0.31}$	$3.65^{+2.61}_{-1.11}$	$0.26^{+0.65}_{-0.21}$	0.87/28

Model 8: Broken Power Law+Fixed Absorption[d]

Γ_1^{a}	Γ_2^{a}	N^{b}	χ_r^2/d.o.f.
1.7[g]	$2.16^{+0.15}_{-0.14}$	$2.45^{+0.44}_{-0.42}$	1.10/28

Model 9: Power Law+Power Law+Fixed Absorption[d]+Gaussian Line

Γ_1^{a}	N_1^{b}	Γ_2^{a}	N_2^{b}	E_L^{h}	E_N^{i}	EW[j]	χ_r^2/d.o.f.
1.7[g]	$0.83^{+0.18}_{-0.83}$	$2.99^{+2.20}_{-0.92}$	$0.60^{+1.25}_{-0.45}$	$6.20^{+0.49}_{-0.40}$	$1.03^{+0.58}_{-0.53}$	650±345	0.45/26

Model 10: Broken Power Law+Fixed Absorption[d]+Gaussian Line

Γ_1^{a}	Γ_2^{a}	N^{b}	E_L^{h}	E_N^{i}	EW[j]	χ_r^2/d.o.f.
1.7[g]	$2.31^{+0.17}_{-0.16}$	$2.63^{+0.38}_{-0.42}$	$6.19^{+0.40}_{-0.36}$	$1.27^{+0.52}_{-0.51}$	575±230	0.53/26

Model 11: Bremsstrahlung+Fixed Absorption[d]+Gaussian Line

kT[k]	N^{b}	E_L^{h}	E_N^{i}	EW[j]	χ_r^2/d.o.f.
$1.58^{+0.37}_{-0.27}$	$2.80^{+0.81}_{-0.69}$	$6.09^{+0.35}_{-0.27}$	$1.72^{+0.47}_{-0.48}$	640±175	0.99/26

[a] Photon index.
[b] Normalization in 10^{-3} photons cm^{-2} s^{-1} keV^{-1} at 1 keV.
[c] Column density in 10^{20} cm^{-2}.
[d] Fixed with the galactic N_H value (4.20×10^{20} cm^{-2}).
[e] Flux in 10^{-12} ergs cm^{-2} s^{-1}.
[f] Luminosity in 10^{44} ergs s^{-1}.
[g] Fixed with the "canonical" value, $\Gamma=1.7$.
[h] Line energy in keV.
[i] Line intensity in 10^{-4} photons cm^{-2} s^{-1}.
[j] Equivalent width in keV.
[k] Plasma temperature in keV.

value ($\Gamma=1.74\pm0.07$) was obtained from the single-power-law fits to the *Einstein* IPC+MPC data (Masnou et al. 1991). Next we fit the LE+ME data using the power law (the value of Γ was fixed with 1.7)+fixed absorption model and the results are presented in Table 2 (see model 6). LE+ME spectra of PHL 909 fitted with model 6 convolved through the detector response is presented in Fig. 3 along with the residuals. Residuals of this figure show the presence of a soft excess in this quasar. *Einstein* results also displayed the presence of a soft excess in this quasar (Masnou et al. 1991 and references therein). To fit this soft excess, two-power-law (model 7) and broken-power-law [with break energy fixed at 0.6 keV following Wilkes et al. (1989)] (model 8) models with fixed absorption were used. The hard spectral index value of models 7 and 8 was fixed with the "canonical" value ($\Gamma=1.7$) and the fit parameters are presented in Table 2.

Recent results obtained from the *EXOSAT* and *Ginga* (Nandra et al. 1989; Leighly et al. 1989; Ghosh and Soundararajaperumal 1991; Piro et al. 1990; Pounds et al. 1989 and references therein) have provided strong evidence for the presence of Fe *K*-shell emission and the absorption line in the X-ray spectra of AGNs. We also find from the residuals of Figs. 1 and 3 that there is a clear indication for the presence of an emission line around 6.0 keV. Therefore, a Gaussian line feature with a fixed width of 0.1 keV and a variable line center was added with models 7 and 8 and were fitted with the spectrum. From χ^2 statistics we find that there was a more positive improvement in the fit than that obtained from models 7 and 8. From the F-test calculations between these two models (models 9 and 10) and models 7 and 8, respectively, with a fixed linewidth, we find that the inclusion of the line is highly significant (>99.9%). The best-fit parameters with 90% confidence error bars are presented in Table 2 (see models 9 and 10). The line center energy is best estimated to be $6.2^{+0.4}_{-0.3}$ keV and the equivalent width of the line ranges between 300 and 1000 eV. Only the statistical errors have been taken into account to estimate the range of the values of the equivalent width. Figure 4 shows the LE+ME spectra with the best-fit model (model 10) con-

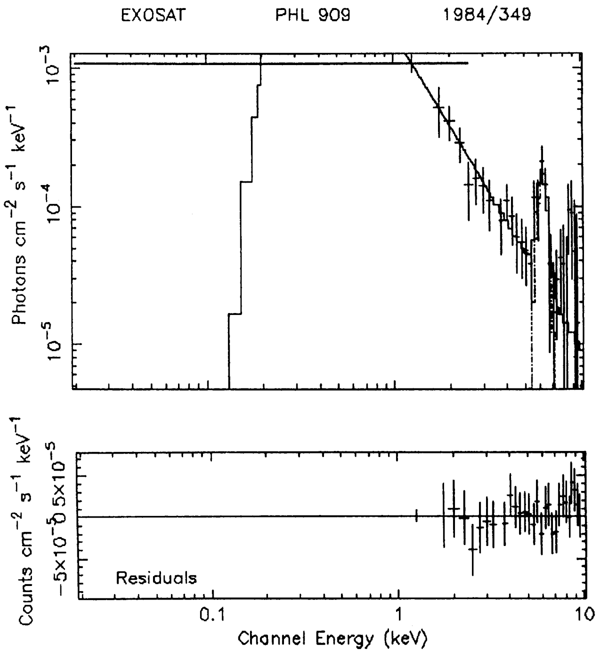

FIG. 4—Same as Fig. 3 but for the broken power law, fixed absorption, and a Gaussian line model.

volved through the detector response, and the residuals between the spectrum and the model are shown in the lower panel of this figure.

The emission line may appear in the spectrum due to the effects of imperfect background subtraction. Thus we carried out independent background subtractions following both the "swap" procedure and the "difference spectra" approaches obtained from the *EXOSAT* Observatory. We found that the emission line persisted in the spectrum of PHL 909. Also, the spectra of this quasar obtained from each half separately, and from the corner detectors (detectors 1, 4, 5, and 8), all displayed the presence of an emission feature around 6 keV.

3.2 Thermal Fits

Next we tried to fit the spectrum using the thermal bremsstrahlung model with fixed absorption, which did not provide an acceptable fit ($\chi^2_r > 2$) to the LE+ME data. However, a good fit to the data was obtained using this model with the Gaussian line component (model 11) and the best-fit parameters are given in Table 2 (see model 11). Results of the F-test computed between this model and model 11 without a Gaussian line show that the inclusion of the Gaussian line with a fixed linewidth is highly significant (>99.9%)

4. DISCUSSION

X-ray flux of PHL 909, which was observed on 1980 July 19, measured with the *Einstein* satellite in the 0.3–3.5 keV band, was $0.32^{+0.03}_{-0.02}\times 10^{-11}$ ergs cm^{-2} s^{-1} (Wilkes and Elvis 1987), and the one obtained from *EXOSAT*, which observed this quasar on 1984 December 14, in the 0.3–3.5 keV range was $0.57\pm0.07\times10^{-11}$ ergs cm^{-2} s^{-1}. These results indicate that the variability between *Einstein* and *EXOSAT* is only about 3.3σ and this does not include the systematic differences due to different instruments and different spectral assumptions. Thus it is suggested that this quasar did not vary between 1980 July and 1984 December. Optical observations of this quasar between 1980 and 1986 displayed a variability of the broad and narrow emission components of H$_\beta$ and Mg II (λ 2798 Å) lines (Zheng and Burbidge 1988). These variations were attributed with the short-lived jet-like structure which may have also influenced the X-ray flux.

From the previous low-energy observation (*Einstein*), it is known that PHL 909 is a flat spectrum source with a photon index value of $1.3^{+0.4}_{-0.3}$ (Wilkes and Elvis 1987). However, the results of our spectrum analysis using single-power-law (model 5: $\Gamma=2.1\pm0.12$), two-power-law (model 9: $\Gamma_2=2.99^{+2.2}_{-0.9}$), and broken-power-law (model 10: $\Gamma_2=2.31\times0.17$) models suggest that this quasar is a steep spectrum source (see Table 2). Again from the *Einstein* observation, Masnou et al. (1991) have detected a soft excess in this quasar. Our results also show the presence of a soft excess in PHL 909 (see Fig. 3). Our spectral index values of this quasar brings PHL 909 into agreement with other radio-quiet quasars and supports the earlier conclusion of Wilkes and Elvis (1987) that radio-quiet quasars have steep X-ray spectra.

The measured energy of the Gaussian line detected in the X-ray spectrum of PHL 909 is in the range 5.9–6.6 keV. Due to the poor resolution of the ME detectors (FWHM at 6 keV is 1.2 keV), it is not possible to make any definite statement regarding the origin of the line (i.e., whether it is due to the redshifted 6.4 keV fluorescent iron line or due to the helium-like 6.7 keV iron line). The measured equivalent width of the emission line is between 300 and 1000 eV. This value is higher than the value usually found in lower luminosity AGN [100–200 eV (Nandra et al. 1989)].

The Fe line in this quasar has a large equivalent width which, if thermal, implies a temperature of 1.6–1.9 keV for the solar abundance usually found for clusters (Edge et al. 1990). The allowed range of plasma temperature obtained from the fits of the thermal bremsstrahlung model (model 11) for PHL 909 is in the range 1.3–1.9 keV, which is in close agreement with the temperature from the iron line equivalent width. The lack of variations of this quasar also allow an extended source, such as a cluster.

Optical images of the PHL 909 host galaxy and field show a significant excess number of galaxies (down to 22 m) in the immediate vicinity of this quasar (Gehren et al. 1984), implying the presence of an Abell-like cluster. Gehren et al. (1984) do not estimate the richness of the cluster X rays may be due to the thermal emission from this cluster of galaxies. There is a correlation between the X-ray luminosity and temperature for clusters (Edge and Stewart 1991). A 7×10^{44} ergs s^{-1} (observed luminosity of PHL 909) cluster would be expected to have a temperature of 2.5–6 keV, which is somewhat higher than but marginally consistent with the derived thermal temperature (1.6 $\pm$0.3 keV). Thus the probability of a thermal origin of the iron line in PHL 909 is real. Since a fraction of the X-ray continuum luminosity is likely to come from the quasar, the thermal luminosity may be in better agreement with the Fe-line equivalent width.

If instead the Fe line is due to the fluorescence of cold iron in the quasar, then the amount of cold matter required is $>5\times10^{22}$ cm^{-2}. We do not detect any such cold matter in the line of sight to this quasar (see Table 2) so a spherical distribution of the fluorescencing material is also not possible.

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