QPOs and Spectral States in GRS 1915+105

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ABSTRACT

We present results from the analysis of X-ray energy spectra and quasi-periodic oscillations (QPOs) from a set of observations which samples a broad range of time variability in GRS 1915+105. We first demonstrate that the frequency and integrated amplitude of a 0.5-10 Hz QPO is correlated with the apparent temperature of the accretion disk for the majority of observations. We then show that the behavior of GRS 1915+105 exhibits two distinct modes of accretion. In the first mode, the QPO is present between 0.5–10 Hz, variability in the source luminosity is dominated by the power law component. In the second mode, the QPO is absent, the changes in the luminosity are dominated by thermal emission from the accretion disk. We find that the color radius and temperature of the inner accretion disk are empirically related by $R_{\text{col}} \propto T_{\text{col}}^{-2} + \text{const.}$ We discuss these results in terms of ongoing efforts to explain the origin of both the QPOs and the hard X-ray component in the spectrum of GRS 1915+105.

Subject headings: black hole physics—stars: individual (GRS 1915+105) — stars: oscillations — X-rays: stars
1. Introduction

GRS 1915+105 is a transient X-ray source that has been extremely active during the six years since it was discovered in 1992 with the WATCH instrument on Granat (Castro-Tirado et al. 1992). It is located behind the Sagittarius arm of the Milky Way at an estimated distance of 12.5 kpc (Mirabel & Rodríguez 1994), where extinction from interstellar dust limits optical/IR studies to wavelengths greater than 1 µm (Mirabel et al. 1994). No measurement has yet been made of a binary mass function or orbital period. GRS 1915+105 is one of several galactic X-ray sources observed to produce superluminal radio jets (Mirabel & Rodríguez 1994, Fender et al. 1999). One of these sources, GRO J1655-40 (Zhang et al. 1997), has been observed optically to be a binary system containing normal F star and a 7 M⊙ compact object presumed to be a black hole (Orosz & Bailyn 1997). Since the spectral properties of GRS 1915+105 are similar to those of GRO J1655-40 (Grove et al. 1998, Remillard et al. 1999), and the luminosity of GRS 1915+105 in outburst is $5 \times 10^{39}$ ergs s$^{-1}$ (25 times the Eddington luminosity of a neutron star; Greiner, Morgan, & Remillard 1996), it is thought that GRS 1915+105 also contains a black hole.

The X-ray spectrum of GRS 1915+105 is typical of a black hole candidate, and spectral models require at least two emission components. The energy spectrum below 10 keV is dominated by emission which appears to be thermal in origin. This is usually modeled with a multi-temperature blackbody representing an optically thick, geometrically thin accretion disk (Mitsuda et al. 1984). The spectrum above 10 keV can be modeled with a power law function, and is thought to originate from inverse-Compton scattering (Sunyaev & Titarchuk, 1980). In the case of GRS 1915+105, this power law component is sometimes seen at energies up to 600 keV (Grove et al. 1998). The physical origin and spatial distributions of the Comptonizing electrons is unknown. It was thought that the electrons were part of an optically thin corona above the plane of the accretion disk, but recent numerical simulations indicate that a self-consistent planar corona cannot produce the spectra seen in the low state of black hole binaries such as Cygnus X-1 (Dove et al. 1998). Various recent models have suggested that the optically thick flow may give way to an optically thin flow close to the black hole in a manner which would produce relativistic electrons (Chen et al. 1995, Chakrabarti & Titarchuk 1995, Luo & Liang 1998, Titarchuk & Zannias 1998, Dove et al. 1998). These Comptonizing electrons could either be extremely hot, or they could be part of a bulk flow of matter streaming toward the black hole. It is also possible that the relativistic electrons are contained in a bulk outflow or a jet.

The X-ray variability of GRS 1915+105 is spectacular (see Figure 1). Observations with BATSE on the Compton Gamma Ray Observatory (Harmon et al. 1994) and with SIGMA on Granat (Finoguenov et al. 1994) have revealed that GRS 1915+105 is highly variable in the hard X-rays. When the Rossi X-Ray Timing Explorer (RXTE) began observations in 1996, variations of as much as 3 Crab were observed on time scales from seconds to days (Greiner, Morgan, & Remillard 1996).

The variations of the X-ray intensity and spectrum on time scales of hundreds of seconds have invited several interpretations. Most models involve a thermal-viscous instability in an accretion disk (Belloni et al. 1997).
1997b) and some take into account the dissipation of accretion energy in a hot corona (Taam, Chen, & Swank 1997). Moreover, some of these cycles of variability in X-rays have been strongly linked to non-thermal flares in the infrared (Sams, Eckart, & Sunyaev 1996, Eikenberry & Fazio 1997, Eikenberry et al. 1998) and in the radio (Mirabel et al. 1998, Fender & Pooley 1998). These studies have produced the first observational evidence that directly links the formation of jets to instabilities in the accretion disk.

Quasi-periodic oscillations (QPOs) seen in power density spectra (PDS) of GRS 1915+105 are another area of interesting research (Morgan, Remillard, & Greiner 1997; Chen, Swank, & Taam 1997). One QPO with a centroid frequency of 67 Hz appears occasionally, and is likely caused by one of several effects due to general relativity in the inner accretion disk. Common lower frequency QPOs (0.001 – 10 Hz) are broadened in frequency by a random walk in phase, and exhibit phase lags of a few percent at \( \sim 10 \) keV relative to 2 keV. The QPO amplitude increases with photon energy, indicating that these QPOs are associated with the hard X-ray power law component. Further studies by Markwardt, Swank, & Taam (1999) and Trudolyubov, Churazov, & Gilfanov (1999) have shown that the frequency of a spectrally hard QPO between 0.5-10 Hz is positively correlated with the thermal flux from the disk. Thus this QPO appears to be linked both to the accretion disk and the population of Compton scattering electrons.

QPOs are therefore a promising means of probing the relationship between the hard and soft components in the spectra of accreting black holes. In this paper we examine the relationship between the properties of the 0.5–10 Hz QPO and X-ray spectral parameters from 27 observations, which sample both steady states and repetitive patterns of variability. We find that the frequency and fractional normalization of the QPO are best correlated with the temperature of the inner accretion disk. We then show that the source has two distinct tracks of spectral evolution, which can be distinguished by the presence or absence of the intermediate frequency (0.5–10 Hz) QPOs. (Note that these QPOs are to be distinguished from the 67 Hz QPO and from the occasional QPOs seen at lower frequency (0.05–0.2 Hz)). We find a relationship between the radius and temperature of the inner disk which spans these two spectral states, and examine the relationship between the photon index of and flux from the power law and the parameters of the inner disk. We conclude that the 0.5–10 Hz QPO is crucial in understanding the origin of the power law component and the variable X-ray emission from GRS 1915+105.

2. Data Selection and Analysis

There have been over 300 observations of GRS 1915+105 by the Proportional Counter Array (PCA) (Jahoda et al. 1996) and the High-Energy X-ray Timing Experiment (HEXTE) (Rothschild et al. 1998) on the Rossi X-ray Timing Explorer (RXTE). In this paper, we report on our studies of selected observations (see Table 1). These observations represent 15% of the time spent observing GRS 1915+105 with the PCA and HEXTE through December 1998. Although these observations are not representative of the amount of time GRS 1915+105 spends in any one state, they cover all types of variability seen to date.

Figure 1 displays X-ray light curves, PCA hardness ratios (HRs), and “dynamic power
spectra” (dynamic PDS) which are demonstrative of the types of variability in the observations listed in Table 1. The light curves represent the count rate in the PCA band (2–30 KeV) per proportional counting units (PCU). The PCA HRs are the count rate at 13-25 keV relative to the rate at 2-13 keV. The dynamic PDS are power density spectra computed every sixteen seconds and rebinned at 0.25 Hz, plotted with time on the horizontal axis, frequency on the vertical axis, and the linear Leahy power density represented by the grey-scale from white (0) to black (> 50).

Figure 1a characterizes the observations on 1996 May 5, 1997 July 20, 1997 November 17, 1998 February 3, and 1998 February 14. These observations have steady count rates and do not exhibit the narrow QPO between 0.5–10 Hz, although low frequency or broad QPOs are present in some of these observations (see Table 1). We find that HR < 0.05 for this set of observations, so we refer to this first set of observations as “soft-steady”.

Figure 1b is representative of the observations during three long time intervals: 1996 July 11 through 1996 August 3; 1996 November 28 through 1997 March 26; and 1997 October 9 through 25. All of these observations have a steady count rate and a strong 0.5–10 Hz QPO. Their spectra are harder (0.08 < HR < 0.15) than the soft-steady group, and Morgan, Remillard, & Greiner (1997) label these as “low-hard states”. Chen, Taam, & Swank (1997) discuss the hardness ratio, count rate, and PDS of the observations in the first time interval, and Trudolyubov, Churazov & Gilfanov (1999) discuss energy spectra and PDS of the observations from the second time interval. The radio flux at 8.3 GHz (or 15.2 GHz for the first interval; see Table 1) distinguishes two subsets in these intervals: the values listed in Table 1 are greater than 35 mJy during the RXTE observations we used from the first and third intervals, but less than 15 mJy during the observations from second interval (there is a radio flare to 110 mJy on 1996 December 6, but there was no coincident RXTE observation on that date). Therefore we refer to the RXTE observations we used from these intervals as the “radio-loud hard-steady” states and “the radio-quiet hard-steady” states respectively. The radio-loud observations are given particular attention later in this paper, as the parameters we derive from spectral fits to these observations are difficult to interpret.

The remainder of the observations exhibit a wide range of variability. Figure 1c is taken from the observation on 1996 October 7. The dips in this observation are spectrally hard and contain a 0.5–10 Hz QPO, while the brighter portions are soft and void of this QPO. Theoretical models of thermal-viscous instabilities in an optically thick accretion disk have been used by Belloni et al. (1997a) to explain this series of dips; based upon spectral analyses they conclude that the inner disk empties and re-fills over the course of each dip.

The light curve in Figure 1d is from the observation on 1997 May 26. The time-series exhibits a QPO throughout the low portion of the light curve in addition to the large quasi-periodic “ringing” flares every ~ 120 s. Taam, Chen, & Swank (1997) have used numerical simulations of an unstable accretion disk which dissipates energy into a hot, optically thin corona to explain many features of these rapid bursts.

The observations on 1997 August 14, 1997 September 9, and 1997 October 30 are similar to the light curve in Figure 1e. The longer
dips are hard, and contain a QPO; the other features lack the 0.5–10 Hz QPO, and are generally soft. These observations are distinct from those represented by Figure 1c: in that they display a large “spike” at the end of the long dips, which is followed by a spectrally soft dip. Observations of this type exhibit infrared and radio flares which follow the X-ray dip-spike cycle (see references in introduction). The hard X-ray dips can also be explained by the inner disk emptying and refilling. The observation on 1997 September 9 has been analyzed by Markwardt, Swank, & Taam (1999) as well, in a manner similar to this paper.

The light curve in Figure 1f is from the observation on 1997 September 16. The dip/flare cycles have properties which are the reverse of cases 1e and 1c, in that the lowest dips in the observation have soft spectra and lack a 0.5–10 Hz QPO, while the brighter portions are spectrally harder and contain a QPO. Spectral analyses indicate that these patterns are not consistent with the disk instability model of Belloni et al. (1997b).

High-luminosity soft states are presented in Figure 1g (from 1997 August 13) and Figure 1h (representative of 1997 August 19 and 1997 December 22). None of these observations contain a narrow 0.5–10 Hz QPO. The observation in Figure 1g is presented in Remillard et al. (1998) in a discussion of the similarities between GRS 1915+105 and GRO J1655-40.

Figure 1i illustrates a moderately soft and bright interval from the observation on (1997 September 18). During the course of the observation, the count rate increases and the spectrum softens on time scales longer than the RXTE orbit for which data is displayed. This observation exhibits the 0.5–10 Hz QPO, which is particularly strong at lower count rates and higher HR. This observation also presented some problems with spectral fits, which we will address later in this paper.

Finally, the observation in Figure 1j displays another type of X-ray ringing (1997 May 18). It exhibits a series of soft flares (∼100 seconds long) that recur with increasingly longer time intervals and lower amplitudes, until the series terminates in a long (1000 s), hard minimum in the count rate. Thereafter, the cycle begins again. The 0.5–10 Hz QPO is present throughout the observation.

In order to create energy spectra and PDS with good statistics while avoiding the intrinsic changes due to the chronic variability of GRS 1915+105, we separate the observations into three categories that we analyze differently. If the standard deviation in the PCA count rate over the full energy band width (effectively 2–30 keV) in 1 s bins is less than 15% of the mean count rate during every 96 min RXTE orbit of an observation, we collect a single energy spectrum and PDS for each orbit. The resulting interval of on-source exposure time outside of the South Atlantic Anomaly is generally ∼3000 s. If the count rate changes slowly from orbit to orbit, but during a single orbit the variability is less than 15%, we collect energy spectra and PDS every 512 s. If the count rate in each orbit varies by more than 15%, we create energy spectra and PDS every 32 s to track the changes in the light curve. Finally, if the count rate varies by more than 15% during 32 s, the time segment is removed from our analysis. Subsequent to these data selections, each spectrum and PDS is analyzed identically.
2.1. Energy Spectra

We perform fits to the energy spectra from both the PCA (Table 2) and HEXTE (Table 3). We use the standard background subtraction procedures for each instrument, and apply these to 128 channel spectra from the Standard 2 mode of the PCA and 64 channel spectra from the Archive mode of HEXTE. All spectra are first fit in the PCA band alone. We then fit the combined PCA/HEXTE spectra for the steady observations only, because the count rate from GRS 1915+105 in the HEXTE band is too low to analyze with good statistics on 32 s time scales. We also are unable to analyze HEXTE spectra from the steady observations on 1996 May 05, July 11, July 26, or August 03, because the HEXTE clusters were not rocking between source and background positions, and accurate background estimates are not available. This leaves 12 observations for which we provide the results of combined PCA/HEXTE spectral fits (Table 3).

In order to investigate systematic errors in the PCA and HEXTE response matrices (from 1997 October 2 and 1997 March 20 respectively), we have analyzed spectra from the Crab Nebula before modeling more complex spectra from GRS 1915+105. We fit the Crab spectrum with a model consisting of a power law with photo-electric absorption. There is sufficient curvature in the Crab spectrum to prevent an adequate fit over the complete bandwidth of the PCA and HEXTE. However, the power law fit to each instrument is good, and we use the results to identify persistent local features in the residuals of an individual detector unit. To lessen the statistical weight of such features, we add 1% systematic errors to the PHA bins in both the PCA and HEXTE. In spectra from the PCA, there are larger systematic deviations in the residuals below 2.5 keV and above 25 keV, which leads us to limit the energy range for PCA analysis to 2.5–25 keV. Moreover, the spectral fits from PCUs 2 and 3 have systematically larger residuals between 5 and 7 keV than do fits from the other PCUs, which leads us to use only data from PCUs 0, 1, and 4. We use both HEXTE clusters, and we find systematic deviation in HEXTE fits to the crab spectrum below 15 keV, which leads us to limit our analysis of HEXTE spectra to energies greater than 15 keV. The upper limit to fits to HEXTE spectra is determined by the energy above which the source is no longer detectable, which occurs between 30–170 keV depending on the observation.

We have applied many models to our spectral analysis of GRS 1915+105, and we find that 22 out of 27 of the PCA spectra are best fit by the standard disk black body and power law component model. We also needed a Gaussian emission line (with a fixed FWHM of 1.0 keV) to measure iron emission between 6 and 7 keV. When fitting all of our spectra, the column density is fixed to \( N_H = 6.0 \times 10^{22} \) cm\(^{-2}\) of H, which was chosen by allowing the column density to float in several spectral fits and taking the average of the resulting values. Finally, we add a fixed multiplicative constant normalization on each PCU and each HEXTE cluster (when applicable) to account for differences in the effective areas of the detectors. This is the same model that has been used for GRS 1915+105 spectra by Belloni et al. (1997) and Taam, Chen, and Swank (1997).

There are several systematic issues that cause us to use caution when interpreting the absolute values of the parameters quoted throughout this paper. The multi-temperature disk model does not take into account elec-
tron scattering (Ebisawa et al. 1993, Shimura & Takahura 1995) and general relativistic effects at the inner disk (Zhang, Cui, & Chen 1997), which modify the emergent spectrum. It is necessary to correct the observed model parameters for these effects in order to obtain estimates of the physical parameters of the disk. The accuracy of such corrections is largely uncertain. Moreover, the black hole mass is not known, and the temperature and radius of the inner disk appear wildly variable in GRS 1915+105. In light of these problems we refrain from applying any of these corrections until the discussion in Section 4.

The free parameters in our model for the disk emission are the normalization on the disk black body component ($N_{bb}$) and the color temperature of the disk at the inner radius ($T_{col}$). The characteristic radius of the inner disk ($R_{col} = D_{10kpc}\sqrt{N_{bb}/\cos\theta}$ km) is derived from the normalization of the disk black body ($N_{bb}$), assuming a distance of 12.5 kpc ($D_{10kpc} = 1.25$) and an inclination angle ($\theta$) equal to that of the radio jets, 70° (Mirabel & Rodriguez 1994). The total flux from the disk is then $F_{bb} = 1.08 \times 10^{-11}N_{bb}\sigma T_{col}^4$ ergs$^{-1}$cm$^{-2}$s$^{-1}$, where $\sigma$ is the Stephan-Boltzmann constant. Our model parameters for the power law component are the photon index of the power law component ($\Gamma$) and the flux at 1 keV from the hard component ($N_{\Gamma}$). The flux from the power law ($F_{pl}$) is calculated by integrating $1.60 \times 10^{-9}N_{\Gamma}E^{-\Gamma+1}$ from 1 to 25 keV, where $E$ is energy in keV. Finally, our model provides the centroid ($E_{gauss}$) and normalization ($N_{gauss}$) of the Gaussian.

The parameters, fluxes, and reduced chi-squared values for the PCA spectral fits are presented in Table 2. In 21 of the 27 cases the standard spectral model provides the best fit with a reduced chi-squared < 2.0. The observation of 1997 September 18 on average yields a higher value ($\chi^2_\nu = 3.18$), but we find no better alternative model. The remaining five spectra (from the soft-steady observations, identified by the use of $E_c$ in Table 2) are not consistent with our standard model. The reduced chi-squared values for these observations were initially in the range of 3 to 35, and we were forced to adopt an alternative model. After exploring many options, and found that the hard (> 10 keV) emission in these observations falls off as an exponential in energy rather than a power law. Although several more complicated physical models (e.g. the thermal Comptonization model of Titarchuk 1993) also fit these spectra well, we are unable to constrain the extra parameters used in these spectral models with our data. For these five cases we therefore replace the power law with an exponential photon spectrum, $N_{\Gamma}\exp(-E/E_c)$, where $E$ is the photon energy, $E_c$ is the cut-off energy of the exponential, and $N_{\Gamma}$ is flux at 1keV. The flux from the exponential ($F_{exp}$) is calculated by integrating over the energy range 1 to 25 keV. The final reduced chi-squared values for all five of these remaining observations are in the range of 0.5–2.6, and the corresponding disk parameters (e.g. $T_{col}$, see Table 2) are very similar to the range of results for observations in which the hard component is a power law.

We must further note that fits with a disk black body and a power law in 6 of the observations (viz. the 5 observations in the radio-loud hard-steady state, plus many segments of 1997 September 18) yield very small values for the color radius (< 10 km) and high values for the effective temperature of the inner disk (3-5 keV). Similar episodes have also been observed in GRS 1124-68 (Nova Muscae; Ebisu-
sawa et al. 1994), GRO J1655-40 (Sobczak et al. 1999a), and XTE J1550-524 (Sobczak et al. 1999b) in which the disk spectrum appears very hot with a normalization that implies a small characteristic radius. These observations are discussed further in Section 4.

The results for the combined PCA/HEXTE fits are given in Table 3. The high-energy upper limits for these fits ($E_{\text{max}}$) are given in column 2. As noted above, joint PCA/HEXTE fits are statistically meaningful only for long exposures during the steady states in GRS 1915+105. For the soft-steady and radio-loud, hard-steady observations, the results from the PCA/HEXTE fits are consistent with those derived from the PCA alone. However, for the radio-quiet, hard-steady observations, we find that the addition of HEXTE data to our analysis requires that we add to our standard model either a high-energy cut-off to the power law (see Table 3) or a component representing reflection from un-ionized matter (not shown) in order to obtain reduced chi-squared values near 1. The reflection model adds a single free parameter, the relative amount of hard flux which is reflected. Assuming that the inclination of the disk is 70° to the line of sight and that metals in the disk are of Solar abundance, we sometimes find values of the reflection parameter $>1.0$, which is not physically possible. Consequently, we have chosen to use the cut-off power law in characterizing the hard-steady spectra. The addition of a cut-off to the power law introduces a systematic decrease of $\Gamma \sim 0.2$ for the power law, but leaves the disk spectral parameters more or less unchanged.

Our results with a cut-off power law are consistent with those of Trudolyubov, Churazov, & Gilfanov (1999), who noticed a cut-off in the power law became detectable when GRS 1915+105 was at low luminosity throughout 1996 November to 1997 March. The presence of a cut-off in the power law would supplement the results of Grove et al. (1998), who demonstrated that GRS 1915+105 was one of a class of black hole candidates which exhibit power law spectra with slope 2.7 which can extend to 600 keV without a cut-off. If our modification of the model to include a cut-off energy is correct, then Table 2 would imply that two types of cut-off power law (with $E_c \sim 3.5$ and 100 keV) are exhibited by GRS 1915+105. Clearly, more observations in the 100–600 keV range are needed in order to determine whether the power law in GRS 1915+105 evolves as a function of time.

### 2.2. Power Density Spectra

To create power density spectra we use data which effectively covers 2–30 keV with a time resolution of 122 $\mu$s. For data segments longer than 32 s, the light curve is divided into 256 s intervals, and a PDS is created for each interval. The PDS are then averaged for each segment, weighted by the total counts, and the results are logarithmically rebinned and subtracted for dead-time-corrected Poisson noise (Morgan, Remillard, & Greiner 1997; Zhang et al. 1996). The shape of the PDS are as diverse as those in Morgan, Remillard, & Greiner (1997) and Chen, Swank, & Taam (1997). When the energy spectra are analyzed in 32 s intervals, PDS are created for the identical intervals. These spectra are linearly rebinned into 0.25 Hz bins, but otherwise treated as above.

We search for a QPO peak in the PDS by fitting frequency intervals between 0.5–12 Hz with a Lorentzian profile on top of a power-law background continuum. Only features with a $Q > 3$ are considered as candidate...
QPOs. In addition we varied this range when low-frequency noise obviously dominated a portion of the PDS; see Figure 1d, for instance. To compensate for systematic difficulties in fitting the QPO profiles, we estimate the significance of the QPO to be the ratio of its amplitude to the average statistical uncertainty over the QPO width, divided by the square root of the reduced-chi squared value from the fit. We estimate the statistical errors on the parameters of the QPO to be the values of the covariance matrix from the least chi-squares minimization routine. The average uncertainty is ±0.04 Hz in frequency, ±0.04 Hz in width, and ±0.02 in amplitude (which is expressed as an RMS deviation divided by the mean count rate).

In order to investigate changes in the energy spectrum which are correlated with the properties of the 0.5–10 Hz QPO, we separate our database of PCA spectral and QPO parameters into three groups based on the strength of the observed QPOs: (1) definite QPOs, for which the best candidate QPO between 0.5–12 Hz has a significance greater than 6.0; (2) no QPO, for which the best QPO candidate either has a significance less than 2.0 or a significance less than 3 with an amplitude less than 2%; and (3) ambiguous cases not selected with the previous criteria. The third category is ignored in this paper, as the results are inconclusive or of poor quality.

The values for the significances of the QPOs used to define these selection criteria are chosen in order to minimize the number of false assignments among the large number of trial fits. The joint condition on the amplitude and significance of candidate features in category 2 is chosen because many of the PDS contain broad QPOs ($Q < 3$), knees, and curvature in the background continuum that affect the distribution of the amplitudes of marginally significant features.

Out of the 250 ks of exposure time denoted by Table 1, 54% yield QPO detections, 15% show no QPO, and 31% are dropped from further study (including those times when the standard deviation in the count rate is above 15%, so that no QPO search or spectral analysis is performed). The amplitude of the definite QPOs (category 1) is $9 \pm 1\%$ for the PDS covering an RXTE orbit, and $7 \pm 3\%$ for the PDS from 32 s and 512 s intervals. The amplitude of the best candidate feature in the no QPO case (category 2) is $0.6 \pm 0.3\%$ for PDS covering and orbit, and $0.8 \pm 0.8\%$ for the PDS from 32 s and 512 s intervals. The distributions of the “with QPO” and “without QPO” groups are therefore statistically well separated.

We must also note that because the 32 s exposures have limited statistics, we expect that there will be some errors in assigning these data to each of the three groups. The dynamic PDS in Figure 1 demonstrates that the 0.5–10 Hz QPO which dominates the PDS in this frequency range is generally persistent, and varies slowly in frequency so long as the energy spectrum varies slowly. However, in rare instances the QPO disappears in a single 32 s time interval among a series of intervals that otherwise exhibit a persistent QPO. In addition, visual inspections of QPO fits reveal occasions when a QPO is found in low frequency ($< 3$ Hz) noise during a single time interval when there is no evidence in the dynamic PDS of a persistent QPO. Of the ∼ 1000 points plotted in the figures below, we estimate that 50 points may have been mis-categorized in one of these two manners. Finally, we must emphasize that we have restricted our interest to features with
3. Results

In Figures 2–10 we present the results of our analysis of PCA energy spectral and 0.5–10 Hz QPO parameters. The size of the symbol in each plot corresponds to the length of the time interval from which the data point was taken: the large squares correspond to data points taken from entire RXTE orbits, the medium-sized asterisks correspond to data points from 512 s intervals, and the small points correspond to data from 32 s intervals. Most of our conclusions use data in the aggregate, but for the reader who wishes to examine how each type of variability (as explained in Section 2 and illustrated in Figure 1) relates to the figures, we plot each type of variability with a separate color. In our scheme, the most red symbols indicate variability types with the softest spectra, and the blue those with the hardest spectra. The key for the large symbols is as follows: the blue squares are radio-quiet hard-steady observations, the green squares are radio-loud hard-steady observations, and the red squares are soft-steady observations (which were fit with an exponential rather than a power law). Only one observation (1997 September 18; Figure 1i) was analyzed at 512 s intervals; this observation is indicated by medium-sized green asterisks. The color code for the 32 s points is as follows: red points correspond to the observations similar to Figures 1g and h; orange points to Figure 1f; yellow-green to Figure 1c; green points to Figure 1d; blue to Figure 1e; and purple to Figure 1j. Note that few red symbols appear in Figures 2–5, as there is no persistent 0.5–10 Hz QPO evident in these soft observations.

3.1. The Relationship Between QPO and Spectral Parameters

We first use our database of spectral parameters and corresponding 0.5–10 Hz QPO parameters (for the definite QPOs) to explore the correlation between QPO frequency and flux from the disk black body over a larger range of light curves than were studied by Markwardt, Swank, & Taam (1999) and Trudolyubov, Churazov, & Gilfanov (1999). The results are shown in Figure 2. Above 5 Hz, the QPO frequency increases slightly with disk flux, and at frequencies between 0.5–5 Hz the QPOs generally occur at a nearly constant disk flux between 0.2–0.5 × 10^{-8} ergs/cm^2/s. However, four of the variable observations (1996 October 7, 1997 August 14, 1997 September 9, and 1997 October 30) seem to lie off this track at frequencies below 4 Hz. These exceptional data points are from dips during observations which exhibit infrared and radio flares (yellow-green points; see Figure 1e) and observations when spectral analysis indicate the inner disk has been evacuated (yellow-green points; see Figure 1c). The QPO frequency is correlated with the power law flux during some individual observations, even at lower fluxes. However, each observation traces its own track in Figure 2d, and it is difficult to make a generalization of the relationship between power law flux and QPO frequency that is valid for the entire set of observations.

To further investigate the relationship between the 0.5–10 Hz QPO and the disk flux (which is simply proportional to $R_{col}^2 T_{col}^4$) we plot the QPO frequency versus the tempera-
ture and radius of the inner disk in Figures 3a and b respectively. It is apparent that the QPO frequency generally increases with the disk temperature, and decreases with disk radius. The observations with both high inner disk temperature and small radii (green squares and green asterisks) are exceptions to this trend; these points are off the temperature scale with $T_{\text{col}} > 3$ keV in Figure 3a, and approach $R_{\text{col}} = 0$ in Figure 3b. We have compared the relationship between QPO frequency and photon index as well (not shown), finding no apparent correlation between the two parameters. For the majority of the observations (excepting the green squares and asterisks with high $T_{\text{col}}$), the inner disk temperature is clearly the parameter that is most useful in predicting QPO frequency.

We next consider the width and the integrated amplitude of the 0.5–10 Hz QPO as they relate to the spectral parameters. The integrated fractional amplitude is

$$A_{\text{QPO}} = \sqrt{\frac{\pi WH}{2I}},$$

where $W$ is the width of the Lorentzian, $H$ is the maximum value of the Lorentzian in Leahy normalized units, and $I$ is the mean count rate. The coherence parameter, $Q$ is a measure of the relative width of the QPO:

$$Q = \frac{\nu}{W},$$

where $\nu$ is the centroid frequency of the QPO.

Finally, the coherence parameter of the QPO does not appear to be correlated with either component of the flux, and its average value is $Q \sim 10$ (Figure 3). Similarly, there is no correlation between either $T_{\text{col}}$ or $R_{\text{col}}$ (not shown), in direct contrast to the variations in the frequency and amplitude of the QPO. We note however that features in the power spectrum that could be interpreted as very broad QPOs ($Q < 3$) have been excluded from consideration here.

### 3.2. Comparison of Spectra with and without QPOs

We next turn our attention to the systematic changes that may occur when the 0.5–10 Hz QPO appears on or off. Figure 4 demonstrates that the correlation between disk black body flux and power law flux are strikingly different when the QPO is present as opposed to when it is not. When the QPO is present, the power law flux is much more variable than the disk flux. For the most part, the changes in the total flux track vertically in this diagram with a relatively constant disk black body flux $(0.3–1.3 \times 10^{-8}$ ergs/cm$^2$s) and varying power law flux $(0.5–13 \times 10^{-8}$ ergs/cm$^2$s). The points at the minimum power law flux correspond to the lowest count rates during hard dips, such as those in Figure 1c (yellow-green points). The vertical tracks are traced by the changing power law flux during the entry into and exit from hard dips, such as those in Figures 1e and j (blue and purple points). There are also several horizontal branches in Figure 4b, which represent the change in disk flux that occurs during the bright, hard emission such as in Figure 11.
(orange points). On the other hand, no steady observation (green and blue squares; Figure 1a) that contains a QPO is seen with a disk black body flux greater than $0.5 \times 10^{-8}$ ergs/cm$^2$/s. This indicates that when the 0.5–10 Hz QPO is present, changes in luminosity are basically confined to changes in the power law component. Substantial increases in the disk flux only occur when the disk structure is cycling through unstable configurations.

When the QPO is absent, the black body component is much more variable than the power law. In most cases, the flux in the power law component remains between 2–5 $\times 10^{-8}$ ergs/cm$^2$/s (less than half of the maximum), while the flux from the disk is seen to vary between 0.7–6 $\times 10^{-8}$ ergs/cm$^2$/s. The horizontal track in Figure 7b corresponds to the soft emission that follows the hard dips during the observations similar to those in Figures 1f and e (the small yellow-green and blue points respectively). However, the soft dips of 1997 September 16 (orange points; Figure 1f), the variable high luminosity soft states (red points; Figures 1k and h), and the soft-steady observations (red squares; Figure 1b) also lie on this same track. Our interpretation of Figure 7b is that the absence of the 0.5–10 Hz QPO corresponds to an accretion mode in which changes in the luminosity are primarily seen in the thermal component of the spectrum.

Having found a fundamental difference in the spectrum of GRS 1915+105 when the 0.5–10 Hz QPO is present and absent, we now examine how these changes manifest themselves in the soft X-ray component of the spectrum. Figure 8 demonstrates that the inner color radius and temperature of the disk are well correlated, even when comparing wildly different observations. The correlation is even more compelling if one ignores those points from segments with small inner disk radii and large temperatures, many of which lie off beyond the extent of the x-axis at temperatures greater than 3 keV (green asterisks and green diamonds; compare Table 1). Plotted on top have much higher amplitudes that the upper limits for the “no QPO” group. At higher fluxes however, our upper limits ($\sim 0.6\%$) are only a factor of a few smaller than the faintest QPOs which we can detect with certainty. Nonetheless, several indications lead us to believe that the 0.5–10 Hz QPO truly is absent along the whole horizontal branch in Figure 1b. We have visually inspected both dynamic PDS (as in Figure 1) and individual PDS integrated for longer times (as in Morgan, Remillard, & Greiner 1997) for all of our observations, and it is clear that the power spectrum differs dramatically during the two accretion modes. Furthermore, if we plot all of our data regardless of QPO properties (not shown), the two accretion modes which we report are still evident— searching for the 0.5–10 Hz QPO only serves to choose one branch or the other other. Since the branch without the QPO is continuous from low disk black body fluxes (where the QPO can clearly be detected) to high fluxes, we feel it is reasonable to believe that the 0.5–10 Hz QPO is genuinely absent from the accretion mode in which we do not detect this QPO.

Having found a fundamental difference in the spectrum of GRS 1915+105 when the 0.5–10 Hz QPO is present and absent, we now examine how these changes manifest themselves in the soft X-ray component of the spectrum. Figure 8 demonstrates that the inner color radius and temperature of the disk are well correlated, even when comparing wildly different observations. The correlation is even more compelling if one ignores those points from segments with small inner disk radii and large temperatures, many of which lie off beyond the extent of the x-axis at temperatures greater than 3 keV (green asterisks and green diamonds; compare Table 1). Plotted on top have much higher amplitudes that the upper limits for the “no QPO” group. At higher fluxes however, our upper limits ($\sim 0.6\%$) are only a factor of a few smaller than the faintest QPOs which we can detect with certainty. Nonetheless, several indications lead us to believe that the 0.5–10 Hz QPO truly is absent along the whole horizontal branch in Figure 1b. We have visually inspected both dynamic PDS (as in Figure 1) and individual PDS integrated for longer times (as in Morgan, Remillard, & Greiner 1997) for all of our observations, and it is clear that the power spectrum differs dramatically during the two accretion modes. Furthermore, if we plot all of our data regardless of QPO properties (not shown), the two accretion modes which we report are still evident— searching for the 0.5–10 Hz QPO only serves to choose one branch or the other other. Since the branch without the QPO is continuous from low disk black body fluxes (where the QPO can clearly be detected) to high fluxes, we feel it is reasonable to believe that the 0.5–10 Hz QPO is genuinely absent from the accretion mode in which we do not detect this QPO.
of the data in Figure 8 is a line corresponding to the function \( R_{\text{col}} = 39T_{\text{col}}^{-2} + 22 \), which represents a least-chi squares fit of the dependence of radius on temperature (the fit excludes the observations with abnormally small \( R_{\text{col}} \) and large \( T_{\text{col}} \)). We believe that the form of this relationship is more instructive than the parameter values themselves, as these parameters may be systematically dependent on the methods used to model the energy spectrum (e.g. the choice of an absorption column) at low \( T_{\text{col}} \), and because some of the spectral evolution may be due to extrinsic changes, such as modifications in the spectrum due to electron scattering. The \( T_{\text{col}}^{-2} \) dependence of \( R_{\text{col}} \) indicates a constant disk flux at low color temperatures, which is seen clearly in Figure 7a. Notice also that the color radius is observed to be relatively constant when the QPO is absent (Figure 7b), although even then there is significant scatter in the data around our empirical correlation.

Finally, we examine the relationship between the inner disk and the power law component of the spectrum. Figure 8 demonstrates that when the 0.5–10 Hz QPO is present, the flux from the power law component generally increases from \( 0.5 - 15 \times 10^{-8} \) ergs/cm\(^2\)/s as the color temperature of the inner disk increases from 0.7–1.9 keV. There are, however, exceptions to this trend. The horizontal branch at \( \sim 3 \times 10^{-8} \) ergs/cm\(^2\)/s of power law flux is composed of the ringing observation on 97 May 26 (Figure 9i) and the ringing portion of the observation on 97 May 18 (Figure 9j). There is a second horizontal branch at \( \sim 9 \times 10^{-8} \) ergs/cm\(^2\)/s of power law flux which is corresponds to the observations with unusually small inner disk radii and large temperatures (green squares and green asterisks), and extends the scale of the plot at high temperatures. When the QPO is absent, the power law flux is generally weaker, and there is little correlation between the power law flux and color temperature.

Figure 10 investigates the relationship between power law index and disk color temperature. When the QPO is present the photon index of the power law component increases from 2.1–3.0 as the color temperature of the inner disk increases from 0.7–2.0 keV. The observations with unusually small inner disk radii lie off the plot at \( T_{\text{col}} > 3.0 \) keV and \( 2.6 < \Gamma < 3.1 \). When the QPO is absent, there is no correlation between the temperature of the inner disk and the photon index.

There are related correlations between the inner radius of the disk and the flux and photon index of the power law, as would be expected given the correlation between radius and temperature, but these correlations (not shown) are weaker. We therefore conclude that when the 0.5–10 Hz QPO is present, the temperature of the inner disk can be used to roughly predict the photon index and the flux from the power law.

4. Discussion

Several of the results of this paper demonstrate the significance of the 0.5–10 Hz QPO in GRS 1915+105. First, we have shown that the frequency of the QPO is best correlated with the temperature of the inner accretion disk (Figure 3). This indicates that the time scale of this QPO is set by conditions in the optically thick accretion disk.

Second, we have discovered that when the 0.5–10 Hz QPO is present, changes in the luminosity of GRS 1915+105 occur mainly in the power law component, and that when the QPO is absent changes in luminosity occur in
the thermal emission from the inner accretion disk (Figure 7). Chen, Swank, & Taam (1997) and Markwardt, Swank, & Taam (1998) have similarly noted that the 0.5–10 Hz QPO is characteristic of hard spectral states. Moreover, when the QPO is absent during the steady observations (where good statistics are available) we find that the hard X-ray component must be modeled with an exponential that produces negligible flux above $\sim 50$ keV, suggesting that the mechanism generating the Comptonizing electrons is inhibited or that the electrons have been quenched by Compton cooling. These results further establish the link between the 0.5–10 Hz QPO and the hard X-ray power law component in GRS 1915+105, as Morgan, Remillard, & Greiner (1997) have already demonstrated that the fractional amplitudes of four QPOs increase with photon energy, extending well past the thermal component of the spectrum.

Two general classes of models for the formation of QPOs are relevant in seeking an understanding of the intimate relationship between the 0.5–10 Hz QPO and both components of the X-ray spectrum of GRS 1915+105. First, numerous authors have proposed that oscillations in the inner accretion disk could lead to QPOs (e.g. Chen & Taam 1994, Abramowicz, Chen, & Taam 1995), and it has recently been noted that if these oscillations generate “seed” photons for Comptonization, the QPO may be predominately exhibited in the hard portion of the energy spectrum (Shrader & Titarchuk 1998). However, the 0.5–10 Hz QPO in GRS 1915+105 disappears when the disk appears stable (in terms of the color radius, as in Figure 3b) and luminous (Figure 7), and there is no clear reason why the hypothesized disk oscillations should cease at these times.

The second class of models postulates that QPOs may form at a geometric boundary between the optically thick disk and the population of Comptonizing electrons, allowing for simultaneous modulations of both the hard and soft components of the spectrum. Models which involve a shock front between the optically thick and thin regions of the accretion flow can provide such effects. Oscillations in the height and width of the shock could result in QPOs by modulating either the number of “seed” photons or the populations of Comptonizing electrons (Kazanas, Hua, & Titarchuk 1997). However, the time scales of such oscillations are on the order of $\sim 100$ Hz, and better serve as an explanation of the 67 Hz feature seen in GRS 1915+105 (Titarchuk, Lapidus, & Musimov 1998). Nonetheless, numerical simulations by Molteni, Sponholz, & Chakrabarti (1996) indicate that oscillations in the radial position of a shock could generate a $\sim 1–10$ Hz QPO. These oscillations are based on a resonance between the cooling time of the shock and the free fall time of matter into the black hole, so the time scale is set by the radius at which the shock forms. The radius is in turn set by the accretion rate in the disk, so the correlation between $T_{\text{col}} (\propto \dot{M}/R^{3})^{1/4}$ and QPO frequency in Figure 3 may support some aspects of this model.

In order to most simply explain the fact that the power law is only active when the 0.5–10 Hz QPO is present, one may hypothesize that the same mechanism generates both the QPO and the relativistic electrons responsible for the hard X-rays in GRS 1915+105. On the other hand, a 9–30 Hz QPO with similar spectral characteristics in GRO J1655-40 decreases in frequency with X-ray luminosity and disk temperature (Remillard et al. 1999).
Sobczak et al. 1999a), precisely the opposite of the QPO is GRS 1915+105 (Figures 2 and 3). If some QPOs are indeed part of the mechanism generating Comptonizing electrons, it is not clear why such a discrepancy would exist between two apparently similar sources.

The results contained in Figure 8 contribute to further reasons for caution in using the disk color radius to estimate the radius of the last stable orbit in accreting black hole systems (Zhang, Cui, & Chen 1997). We have demonstrated that the disk color radius approached a stable value only when the 0.5–10 Hz QPO is absent. If we omit the points at $T_{\text{col}} < 1.2$ keV as likely statistical “leaks” which are mis-categorized as lacking a QPO, we find a minimum stable color radius, $R_{\text{col,min}} = 44 \pm 8(1\sigma)$ km (the uncertainty here is standard deviation of the values for $R_{\text{col,min}}$ used to compute the average, which by coincidence is equal to our average uncertainty on a single measurement of $R_{\text{col}}$). Note that even after this careful selection of data, there is still a 20% scatter in color radius values, which should be considered in addition to the uncertainty on the particular correction factors from which a physical radius is estimated from the values of $R_{\text{col}}$. If we now use Equation 3 in Zhang, Cui, & Chen (1997) along with their correction factors to convert our estimate of $R_{\text{col,min}} = 44 \pm 8$ to an estimate of the last stable orbit, we find the compact object in GRS 1915+105 has a mass $M \sim 14 \pm 4M_\odot$ km for a Schwarzschild black hole, $M \sim 65 \pm 20M_\odot$ for a prograde Kerr black hole, and $M \sim 9\pm 3M_\odot$ for a retrograde Kerr black hole. However, we note that significant uncertainty in this estimate of the mass is introduced not only through the unknown spin period, but also through systematic difficulties in determining the disk parameters (e.g. Sobczak et al. 1999a).

The radio-loud hard-steady observations with $R_{\text{col}} < 10$ km deserve further consideration, as they provide exceptions to many of the global trends in Figures 2-10. In addition to the exceptional values of $R_{\text{col}}$ and $T_{\text{col}}$ in Table 2, these observations exhibit particularly strong iron emission in the energy spectrum ($N_{\text{gauss}} > 8.5 \times 10^{-2}$). Moreover, these radio-loud hard-steady observations are distinct from the radio-quiet observations, in that joint PCA/HEXTE fits reveal no necessity for either a reflection component or a cut-off in the power law (Table 3). The time intervals when the radio-loud hard-steady observations occurred (1996 July–August and 1997 October) have also been singled out as exhibiting optically thick radio emission, and the intervals are referred to as the “plateau” radio state by (Fender et al. 1999; see also references therein). It is evident that these time intervals deserve additional attention, not only to explore the limits of the the multi-temperature disk model in the X-ray band, but also to elucidate the relationship between emission from GRS 1915+105 in the X-ray and radio wavelengths.

Finally, our accretion modes may be compared with the “states” which Belloni et al. (1997b) via Figure 7 used to characterize the variable emission from GRS 1915+105. The “quiescent” state of Belloni et al., which corresponds to hard dips such as those in Figure 1c, is associated with the accretion mode described in Section 3.2. The “flaring” state of Belloni et al. describes the soft, bright emission that follows the hard dips (Figure 7a; see also the discussion in Section 3.2). The “flaring” state of Belloni et al. describes the soft, bright emission that follows the hard dips (Figure 7a), and is associated with the accretion mode without the QPO. We also find that the fluxes taken from steady obser-
vations (large squares in Figure 7) when the emission from GRS 1915+105 was stable for entire orbits (> 3000 s) lie on very similar tracks as the fluxes derived from 32 s intervals (small points) when the source was highly variable. This suggests an alternative perspective for understanding the cyclic variations in GRS 1915+105. The variations may represent transitions between two quasi-steady accretion modes, signified by the presence or absence of the 0.5–10 Hz QPO. This concept may be useful toward understanding the “reverse” dip cycles represented in Figure 1f (orange points in Figure 7), which are not understood in the context of the CV-like disk instability model (Belloni et al. 1997a). The physics underlying these accretion modes is unknown, but the transitions may require an explanation beyond the traditional thermal disk instability.

5. Conclusions

We have analyzed a set of 27 PCA observations of GRS 1915+105 which are a representative sample of the spectral shapes and variability patterns from this source. We modeled the energy spectrum with a disk black body, a Gaussian, a constant interstellar absorption, and either a power law or exponential spectrum. We also searched the PDS for a 0.5–10 Hz QPO. Finally, we compared the parameters of this QPO with the spectral parameters, and separated our database into two groups based upon whether or not they contained this QPO.

We extended the results of Markwardt, Swank, & Taam (1999) and Trudolyubov, Churazov, & Gilfanov (1999) by demonstrating that the 0.5–10 Hz QPO serves as a marker for two distinct accretion modes (Figure 7). When the QPO is present, accretion energy is channeled primarily into the power law component of the spectrum and the power law flux and spectral index roughly increase as the temperature of the disk increases. When the QPO is absent, accretion energy is primarily expressed in the disk black body component, while the power law flux and photon index are largely uncorrelated with the disk color temperature (Figures 7, 8, and 11).

The color radius and temperature of the inner accretion disk are related by \( R_{\text{col}} \propto T_{\text{col}}^{-2} + \text{const} \), and that when the QPO is absent, the color radius remains near a minimum value of \( R_{\text{col,min}} = 44 \pm 8(1\sigma) \) km. Assuming this minimum value of the color radius is indicative of the innermost stable orbit, rough estimates of the mass of the black hole in GRS 1915+105 range between \( \sim 6-80 \) M/M\( _{\odot} \), depending on the spin.

Eleven of the 27 observations require particular attention in modeling their spectra. Six observations (with a hard spectrum and 0.5–10 Hz QPO) are characterized by relatively high radio flux, high color temperatures, and color inner disk radii less than 5 km. The reduced chi-squared values for the spectral fits are good, but there is no physical interpretation of the dramatic decrease in the normalization of the thermal component.
In five other observations that have soft spectra and lack the narrow 0.5–10 Hz QPO, the hard component must be modeled with an exponential function.

Finally, we find that much of the emission from GRS 1915+105 can be reduced to two accretion modes, distinguished by the presence or absence of a 0.5-10 Hz QPO.

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Fig. 1.— Light curves, PCA HRs, and dynamic PDS of GRS 1915+105 from the PCA on RXTE. Light curves (top panels) are the count rate per second per PCU. We have not corrected for PCA dead time, which introduces an error of 10% per 5000 counts/s/PCU. The PCA HRs (middle panels) are the count rate at 13-25 keV relative to the rate at 2-13 keV. The dynamic PDS (bottom panels) are power density spectra computed every sixteen seconds and rebinned at 0.25 Hz, plotted with time on the horizontal axis, frequency on the vertical axis, and the linear Leahy power density represented by the grey-scale from white (0) to black (> 50). A QPO in the PDS appears as a dark horizontal band.
### Table 1
#### Summary of Selected Observations

| Observation ID | Date        | Exposure (sec) | C/s per PCU | Variability (σ/mean) | Interval | Radio Flux | QPO |
|----------------|-------------|----------------|-------------|----------------------|----------|------------|-----|
| 10408-01-06-00 | 1996 May 05 | 10020          | 3264        | 0.077                | orbit    |            | No  |
| 10408-01-22-00 | 1996 Jul 11 | 2700           | 2107        | 0.038                | orbit    | 0.050      | Yes |
| 10408-01-27-00 | 1996 Jul 26 | 9420           | 1777        | 0.083                | orbit    | 0.090      | Yes |
| 10408-01-28-00 | 1996 Aug 03 | 11280          | 1723        | 0.079                | orbit    | 0.100      | Yes |
| 10408-01-38-00 | 1996 Oct 07 | 11280          | 3337        | 0.572                | 32 s     | 0.003      | Yes |
| 20402-01-04-00 | 1996 Nov 28 | 7020           | 2142        | 0.126                | orbit    |            | Yes |
| 20402-01-13-00 | 1997 Jan 29 | 10620          | 952         | 0.076                | orbit    | 0.007      | Yes |
| 20402-01-14-00 | 1997 Feb 01 | 9900           | 922         | 0.075                | orbit    | 0.006      | Yes |
| 20402-01-15-00 | 1997 Feb 09 | 10500          | 831         | 0.086                | orbit    |            | Yes |
| 20402-01-16-00 | 1997 Feb 22 | 6060           | 821         | 0.077                | orbit    | 0.014      | Yes |
| 20402-01-21-00 | 1997 Mar 26 | 3660           | 865         | 0.073                | orbit    | 0.003      | Yes |
| 20402-01-28-00 | 1997 May 18 | 8100           | 1521        | 0.451                | 32 s     |            | Yes |
| 20402-01-30-00 | 1997 May 26 | 4260           | 1836        | 0.298                | 32 s     | 0.010      | Yes |
| 20402-01-38-00 | 1997 Jul 20 | 7620           | 3853        | 0.113                | orbit    | 0.009      | No  |
| 20186-03-03-00 | 1997 Aug 13 | 9900           | 4540        | 0.270                | 32 s     | 0.013      | No  |
| 20186-03-03-01 | 1997 Aug 14 | 9900           | 3567        | 0.654                | 32 s     | 0.050      | Yes |
| 20402-01-41-00 | 1997 Aug 19 | 2340           | 4880        | 0.159                | 32 s     | 0.009      | No  |
| 20402-01-45-03 | 1997 Sep 09 | 10800          | 2539        | 0.527                | 32 s     | 0.051      | Yes |
| 20186-03-02-03 | 1997 Sep 16 | 20280          | 3696        | 0.365                | 32 s     | 0.105      | Yes |
| 20186-03-02-06 | 1997 Sep 18 | 27360          | 3504        | 0.300                | 512 s    | 0.019      | Yes |
| 20402-01-49-01 | 1997 Oct 09 | 4900           | 1796        | 0.043                | orbit    |            | Yes |
| 20402-01-52-00 | 1997 Oct 25 | 18180          | 1543        | 0.057                | orbit    | 0.051      | Yes |
| 20402-01-52-01 | 1997 Oct 30 | 2100           | 3130        | 0.613                | 32 s     | 0.156      | Yes |
| 20402-01-55-00 | 1997 Nov 17 | 8800           | 3554        | 0.080                | orbit    | 0.028      | No  |
| 20402-01-60-00 | 1997 Dec 22 | 12540          | 5436        | 0.159                | 32 s     | 0.013      | No  |
| 20402-01-04-00 | 1998 Feb 03 | 6420           | 2086        | 0.077                | orbit    | 0.006      | No  |
| 30703-01-08-00 | 1998 Feb 14 | 4920           | 1195        | 0.054                | orbit    | 0.020      | No  |

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*a* Radio points were interpolated from radio observations within 8 hours of the X-ray observation. Radio fluxes are at a frequency of 8.3 GHz, from public domain data from the NSF-NRAO-NASA Green Bank Interferometer, unless otherwise indicated.

*b* The QPO here is the one between 0.5-10 Hz with a $Q$ of about 10, unless otherwise indicated.

*c* 15.2 GHz from the Ryle Telescope, estimated from Figure 4 of Pooley & Fender (1997).

*d* The QPOs here are either below 0.1 Hz, have $Q$ less than 2, or both. We do not discuss these QPOs in this paper.
Table 2
PCA Fits to a Model of Absorption, DISKBB, Power Law or Exponential, and Gaussian

| Date    | DBB Flux | Hard Flux | Hard/ DBB | $\Gamma$ | $E_c$ | $N_l$ | $T_{col}$ | $R_{col}$ | $E_{gauss}$ | $N_{gauss}$ | $\chi^2$/$\nu$ |
|---------|----------|-----------|-----------|----------|------|------|----------|----------|-------------|-------------|--------------|
| 1996 May 05 | 2.6 | 2.3 | 0.88 | ... | 3.28 | 1.4 | 1.38 | 55 | 6.5 | 3.2 | 1.02 |
| 1996 Jul 11 | 0.2 | 8.4 | 12 | 3.15 | ... | 62.1 | 3.87 | 2.1 | 6.0 | 11 | 0.94 |
| 1996 Jul 26 | 0.5 | 3.6 | 2.6 | 2.61 | ... | 15.8 | 4.15 | 2.6 | 6.0 | 13 | 0.97 |
| 1996 Aug 03 | 0.4 | 3.8 | 3.0 | 2.69 | ... | 18.3 | 4.17 | 2.5 | 6.0 | 12 | 0.90 |
| 1996 Oct 07 | 2 | 2.3 | 1.07 | 2.63 | ... | 12.5 | 1.36 | 67 | 6.1 | 3.0 | 1.27 |
| 1996 Nov 28 | 0.4 | 5.8 | 5.3 | 2.63 | ... | 26.7 | 1.13 | 33 | 6.1 | 5.5 | 1.16 |
| 1997 Jan 29 | 0.4 | 2.0 | 1.7 | 2.32 | ... | 6.3 | 0.87 | 55 | 6.4 | 3.4 | 0.76 |
| 1997 Feb 01 | 0.4 | 1.9 | 1.5 | 2.31 | ... | 6.0 | 0.85 | 60 | 6.4 | 3.5 | 0.76 |
| 1997 Feb 09 | 0.3 | 1.7 | 2.1 | 2.15 | ... | 4.2 | 0.72 | 67 | 6.3 | 3.9 | 0.83 |
| 1997 Feb 22 | 0.4 | 1.7 | 1.6 | 2.21 | ... | 4.5 | 0.80 | 61 | 6.4 | 3.4 | 0.80 |
| 1997 Mar 26 | 0.4 | 1.6 | 1.3 | 2.28 | ... | 4.8 | 0.82 | 64 | 6.4 | 3.2 | 0.79 |
| 1997 May 18 | 0.7 | 2.6 | 4.0 | 2.42 | ... | 9.5 | 1.03 | 57 | 6.4 | 1.9 | 1.05 |
| 1997 May 26 | 0.9 | 3.1 | 3.5 | 2.57 | ... | 13.3 | 1.20 | 46 | 6.4 | 1.6 | 1.03 |
| 1997 Jul 20 | 3.4 | 2.0 | 0.59 | ... | 3.23 | 1.3 | 1.49 | 54 | 6.3 | 1.7 | 0.77 |
| 1997 Aug 13 | 5 | 4.0 | 0.82 | 2.69 | ... | 19.5 | 1.80 | 45 | 6.0 | 2.9 | 1.85 |
| 1997 Aug 14 | 2 | 3.5 | 2.4 | 2.58 | ... | 16.3 | 1.13 | 75 | 6.3 | 2.8 | 1.19 |
| 1997 Aug 19 | 5 | 2.8 | 0.64 | 2.87 | ... | 16.5 | 1.79 | 43 | 6.0 | 1.0 | 1.96 |
| 1997 Sep 09 | 1 | 3.8 | 3.5 | 2.78 | ... | 20.7 | 1.24 | 57 | 6.1 | 2.3 | 1.21 |
| 1997 Sep 16 | 1 | 7.8 | 7.0 | 2.89 | ... | 44.1 | 1.52 | 31 | 6.1 | 1.7 | 1.53 |
| 1997 Sep 18 | 0.3 | 11 | 55 | 3.0 | ... | 74.5 | 2.58 | 8 | 6.1 | 7.5 | 2.54 |
| 1997 Oct 09 | 0.3 | 6.7 | 7.5 | 3.12 | ... | 48.0 | 4.82 | 1.6 | 6.3 | 8.7 | 0.67 |
| 1997 Oct 25 | 0.3 | 3.7 | 4.5 | 2.66 | ... | 17.2 | 4.57 | 1.6 | 6.3 | 7.0 | 1.15 |
| 1997 Oct 30 | 0.9 | 5 | 7.0 | 2.63 | ... | 23.0 | 1.11 | 55 | 6.4 | 3.0 | 1.16 |
| 1997 Nov 17 | 2.7 | 2.3 | 0.85 | ... | 3.42 | 1.3 | 1.49 | 48 | 6.4 | 2.7 | 0.50 |
| 1997 Dec 22 | 5 | 2.9 | 0.58 | 2.68 | ... | 14.3 | 1.82 | 44 | 6.0 | 3.4 | 1.87 |
| 1998 Feb 03 | 1.8 | 1.4 | 0.79 | ... | 3.24 | 0.9 | 1.30 | 51 | 6.1 | 6.4 | 1.07 |
| 1998 Feb 14 | 1.6 | 0.5 | 0.29 | ... | 3.46 | 0.3 | 1.10 | 68 | 6.4 | 7.4 | 2.56 |

a All parameters are the averages of the values for each time segment included in the results of Section 3 of this paper. We estimate the error introduced by our spectral fitting procedure by varying an individual parameter (holding the others fixed) for each fit until chi-squared for the spectral fits changes by 2.7, which represents a 90% confidence interval. For PCA spectra collected each satellite orbit or every 512 s, the 90% confidence intervals are typically $\Gamma \pm 0.01$, $N_l \pm 0.4$, $N_{gauss} \pm 0.2 \times 10^{-2}$, and $E_{gauss} \pm 0.06$. For spectra integrated for 32 s, our uncertainty is typically $\Gamma \pm 0.06$, $N_l \pm 4$, $T_{col} \pm 0.08$ keV, $R_{col} \pm 3$ km (or 10%), $N_{gauss} \pm 0.5 \times 10^{-2}$, and $E_{gauss} \pm 0.2$.

b These are unabsorbed values for the flux, calculated as indicated in the text. The units are $10^{-8}$ ergs/cm$^2$/sec.

c Represents either the flux in power law or exponential, depending on the model used.

d Represents either the normalization of the power law or exponential, depending on the model used.
### Table 3
PCA/HEXTE Fits\(^a\) to a Model of Absorption, DISKBB, Cut-Off Power Law or Exponential, and Gaussian

| Date        | Max E\(^b\) | DBB Flux\(^c\) | Hard Flux\(^c\) | \(\Gamma\) | \(E_c\) | \(N_T\) | \(T_{col}\) | \(R_{col}\) | \(E_{gauss}\) | \(N_{gauss}\) | \(\chi^2_\nu\) |
|-------------|-------------|----------------|-----------------|---------|--------|--------|----------|----------|-------------|-------------|-----------|
| 1996 Nov 28 | 150 keV     | 0.6 keV Fluct | 2.49 keV Fluct  | 0.6     | 5.8    | 21.7   | 1.13     | 39 km     | 6.0 keV     | 4.4 \(\times 10^{-2}\) | 1.04       |
| 1997 Jan 29 | 150 keV     | 0.5 keV Fluct | 2.2 keV Fluct   | 0.5     | 2.2    | 4.8    | 0.93     | 52 km     | 6.7 keV     | 2.7 \(\times 10^{-2}\) | 1.03       |
| 1997 Feb 01 | 170 keV     | 0.5 keV Fluct | 2.3 keV Fluct   | 0.5     | 2.3    | 4.5    | 0.90     | 56 km     | 6.7 keV     | 2.8 \(\times 10^{-2}\) | 1.02       |
| 1997 Feb 09 | 170 keV     | 0.3 keV Fluct | 2.0 keV Fluct   | 0.3     | 2.0    | 3.0    | 0.86     | 51 km     | 6.6 keV     | 3.1 \(\times 10^{-2}\) | 1.91       |
| 1997 Feb 22 | 150 keV     | 0.4 keV Fluct | 2.1 keV Fluct   | 0.4     | 2.1    | 3.6    | 0.84     | 55 km     | 6.7 keV     | 2.7 \(\times 10^{-2}\) | 1.08       |
| 1997 Mar 26 | 160 keV     | 0.5 keV Fluct | 2.0 keV Fluct   | 0.5     | 2.1    | 110 keV| 0.86     | 60 km     | 6.6 keV     | 2.5 \(\times 10^{-2}\) | 1.12       |
| 1997 Jul 20 | 50 keV      | 3.5 keV Fluct | 2.0 keV Fluct   | 3.5     | 2.0    | 3.2    | 1.3      | 55 km     | 6.3 keV     | 1.9 \(\times 10^{-2}\) | 0.65       |
| 1997 Oct 09 | 90 keV      | 0.2 keV Fluct | 2.97 keV Fluct  | 0.2     | 6.1    | 37.9   | 4.48     | 1.6 km    | 6.3 keV     | 7.3 \(\times 10^{-2}\) | 1.06       |
| 1997 Oct 25 | 90 keV      | 0.3 keV Fluct | 2.71 keV Fluct  | 0.3     | 4.1    | 18.1   | 4.77     | 1.6 km    | 6.3 keV     | 7.5 \(\times 10^{-2}\) | 1.34       |
| 1997 Nov 17 | 40 keV      | 2.8 keV Fluct | 2.3 keV Fluct   | 2.8     | 2.8    | 3.5    | 1.2      | 47 km     | 6.4 keV     | 1.8 \(\times 10^{-2}\) | 0.71       |
| 1998 Feb 03 | 40 keV      | 1.8 keV Fluct | 1.4 keV Fluct   | 1.8     | 1.4    | 3.2    | 0.9      | 51 km     | 6.1 keV     | 0.6 \(\times 10^{-2}\) | 1.08       |
| 1998 Feb 14 | 30 keV      | 1.6 keV Fluct | 0.5 keV Fluct   | 1.6     | 0.5    | 3.4    | 0.3      | 70 km     | 6.3 keV     | 7.8 \(\times 10^{-2}\) | 3.17       |

\(^a\)The uncertainties on the parameters from combined PCA/HEXTE fits with a cut-off power law are \(T_{col} \pm 0.03\) keV, \(R_{col} \pm 3\) km, \(\Gamma \pm 0.03\), \(E_c \pm 15\), \(N_T \pm 0.3\). When the exponential is used for the hard component, the uncertainties are typically \(T_{col} \pm 0.02\), \(R_{col} \pm 1\) km, \(E_c \pm 0.1\), and \(N_T \pm 0.1\). The errors on the Gaussian are typically \(E_{gauss} \pm 0.1\) and \(N_{gauss} \pm 0.3 \times 10^{-2}\) in all cases.

\(^b\)The maximum energy at which the source dominates the background in the energy spectrum was used as the upper limit for the range the spectral fit was performed on.

\(^c\)These are unabsorbed values for the flux, calculated as indicated in the text. The units are \(10^{-8}\) ergs/cm\(^2\) sec.

\(^d\)Represents either the flux in the power law or exponential, depending on the model used.
Fig. 1.—Figure 1, continued
Fig. 2.— QPO frequency vs. thermal flux from the disk (a) and vs. flux from the power law (b). The key to the symbols is described in the text.

Fig. 3.— QPO frequency vs. the color temperature of the inner disk (a) and vs. the color radius of the inner disk (b). The points with abnormally high temperature (green squares and asterisks) are off the scale of panel a. The symbol key is described in the text.
Fig. 4.— RMS QPO fractional amplitude vs. thermal flux from the disk (a) and vs. flux from the power law (b). The symbol key is described in the text.

Fig. 5.— QPO amplitude vs. the color temperature of the inner disk (a) and vs. the color radius of the inner disk (b). The points with abnormally high temperature are off the scale of panel a. The symbol key is described in the text.
Fig. 6.— QPO coherence \((Q = \nu/\delta\nu)\) vs. thermal flux from the disk (a) and vs. flux from the power law (b). The symbol key is described in the text.

Fig. 7.— Flux from the power law vs. the thermal flux from the disk when the 0.5-10 Hz QPO was present (a) and when the same QPO was absent (b). The symbol key is described in the text.
Fig. 8.— Plots of the color radius of the inner disk vs. the color temperature of the inner disk when the 0.5-10 Hz QPO was present (a) and when the same QPO was absent (b). The lines drawn correspond to $R_{\text{col}} = 39T_{\text{col}}^{-2} + 22$. The points with abnormally high temperature are off the scale of panel a. The symbol key is described in the text.

Fig. 9.— Flux from the power law vs. the color temperature of the inner disk when the 0.5-10 Hz QPO was present (a) and when the same QPO was absent (b). The points with abnormally high temperature are off the scale of panel a. The symbol key is described in the text.
Fig. 10.— Photon index vs. the color temperature of the inner disk when the 0.5-10 Hz QPO was present (a) and when the same QPO was absent (b). The points with abnormally high temperature are off the scale of panel a. The symbol key is described in the text.