THE COMPTON MICROSCOPE: USING THE ENERGY DEPENDENCE OF QPO AMPLITUDES TO PROBE THEIR ORIGIN IN ACCRETION DISKS

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ABSTRACT

We report the development of a new tool to determine the origin of quasi-periodic oscillations (QPOs) in accretion disk systems. The technique uses the source energy spectrum and the energy dependence of the QPO fractional amplitude to restrict the location of the emission region of the modulated photons, which are assumed to originate in the inner accretion disk. Both Monte Carlo and semi-analytical methods are presented. We assume the accretion disk is enshrouded by a slab atmosphere of hot electrons in which unsaturated Compton scattering produces the high-energy spectrum. Properties of the atmosphere, in particular the electron temperature, are assumed functions of radius from the central compact object. We show that our model reproduces the observed energy dependence of the fractional amplitude of the 67 Hz QPO in GRS 1915+105 if the QPO is assumed to originate within five gravitational radii from the innermost stable circular orbit.

Subject headings: accretion, accretion disks — black hole physics — radiative transfer — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

Quasi-periodic oscillations (QPOs) have been seen in the power spectra of X-ray binaries since work with the EXOSAT and Ginga satellites (van der Klis 1995). With the launch of the Rossi X-Ray Timing Explorer (RXTE) satellite in 1995, advances in instrumentation have allowed observers to measure QPOs at such high frequencies that their origin has been associated with the inner regions of the accretion disks which are expected to exist in binary systems. Evidence on the exact location of the QPO generation, however, remains unclear. Observed properties of the QPOs, such as centroid frequency, width, amplitude, phase lag, and coherence, have been investigated for insight into the physical processes which produce these oscillations. Another characteristic of QPOs, the energy dependence of their fractional root-mean-square (rms) amplitude, remains as a relatively unexplored tool to diagnose their origin. In this Letter we report the development of a tool that utilizes the observed energy dependence of the QPO amplitude to locate the accretion disk region in which the modulation may occur.

Analyses of QPO mechanisms must be commensurate with a model for the overall energy spectrum of the source. In particular, a frequent component of X-ray binary spectra is a high-energy power-law, usually interpreted to arise from unsaturated inverse Comptonization by hot electrons. These electrons are typically associated with a high-temperature atmosphere or corona for which the geometry, production, and physical properties are uncertain (Dove, Wilms, & Begelman 1997, and references therein). Here we demonstrate a method for localizing the QPO emission site using the observed energy dependence of the QPO amplitude and the observed source energy spectrum. We assume a particular form of a Comptonizing atmosphere which adequately fits the observed source spectrum. Ideally one would like to constrain the atmosphere’s true structure by employing additional observed properties of the QPO, but this is beyond the scope of this Letter.

2. COMPTONIZING MODEL

To demonstrate the qualitative effects of a Comptonizing atmosphere on the energy dependence of QPO fractional amplitudes we consider a simple model of an accretion disk enshrouded by a steady-state, locally plane-parallel corona. The corona consists of thermalized, nonrelativistic hot electrons which are optically thin to absorption and have no bulk motion. In addition, properties of the atmosphere, such as the electron temperature \( T_e \), may vary slowly in the radial direction along the surface of the accretion disk. Photons originate in the cold accretion disk, which has temperature profile \( T_0(r) \), and scatter through the slab atmosphere before escaping the cloud or re-entering the disk to be absorbed. Here we do not consider the effects of strong gravity on photon paths.

A measure of the distortion of a photon spectrum by Compton scattering through a nonrelativistic thermal distribution of electrons is given by the Compton \( y \) parameter,

\[
y = \frac{4kT_e}{m_e c^2} \max(\tau_e, \tau_c^2),
\]

where \( m_e c^2 \) is the electron rest energy and \( \tau_e \) is the optical depth of the cloud. If we restrict our cloud parameters such that \( y(r) \ll 1 \), then the spectral profile of the observed photon energy \( E \) is described in the range \( kT_e \ll E \ll kT_c \) by unsaturated Comptonization of a soft photon input (Rybicki & Lightman 1979). The emergent photon flux density in this regime is given by a power-law dependence,

\[
dN/dE \propto E^{-\alpha},
\]

where

\[
\alpha = -\frac{1}{2} + \left( \frac{9}{4} + \frac{4}{3} \right)^{1/2} \approx 2y^2 - \frac{1}{2} + O(y^2),
\]

and \( N \) has units of photons cm\(^{-2}\) s\(^{-1}\).

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If we choose the radial gradient of the electron temperature such that $y$ decreases with $r$, then it follows from equations (1)–(3) that $\alpha(r_1) < \alpha(r_2)$ if $r_1 < r_2$. That is, simply, photons which originate near the inner edge of the accretion disk are more strongly Comptonized than photons which originate in the outer regions of the disk. If we apply the above to a QPO which originates generally inside the radius at which the maximum (unmodulated) luminosity per unit radius is emitted from the disk, the QPO fractional amplitude can be an increasing function of energy. More particularly, the QPO amplitude may continue to increase over a domain which includes energies that are too high to be traditionally associated with “thermal” processes from the relatively cold disk.

3. MONTE-CARLO SIMULATIONS

One approach to quantitatively assess the above approach is to conduct Monte Carlo simulations which numerically propagate accretion disk photons through a Comptonizing corona. In our simulations we adopt the standard semi-relativistic thin disk model of Shakura & Sunyaev (1973) with the modified Newtonian potential (Nowak & Wagoner 1991)

$$\Phi = -(GM/r)[1 - 3(GM/rc^2) + 12(GM/rc^2)^2],$$

where $M$ is the mass of the central black hole. With this choice of potential the disk temperature is given by (Nowak 1992)

$$T_0(r) = 10.286 T_m r^{-4} \left( \frac{1 - \frac{8}{r} + \frac{60}{r^2}}{1 - \sqrt{\frac{6}{r - 6 + 36/r}}} \right)^\frac{1}{4},$$

where the radial coordinate is now in units of $GM/c^2$ and the maximum temperature $T_m$ of the disk is reached at the radius $r = 9.795$. The electron temperature of the atmosphere is taken to be

$$T_e(r) = T_0(r/r_e)^{-1},$$

where $r_e$ is the inner radius of the disk and $T_0$ is a constant. We assume the accretion disk extends down to the innermost stable circular orbit $r_{ms}$ such that $r_e = r_{ms} = 6$ for our assumed slowly rotating black hole. To completely specify a model spectrum (minus an overall normalization), we must choose $T_m$, $T_0$, and the optical depth $\tau$ of the electron cloud. Finally, an additional parameter $r_e$ depicts the outer radius of the electron cloud, which is not constrained to cover the entire disk.

The simulation code for the slab model is based on the “particle escape weighting” algorithm presented by Pozdnyakov, Sobol, & Sunyaev (1983). A brief description of the central driver of the code has been given by Nowak et al. (1999). Photons are created with a disk-blackbody energy distribution and undergo repeated Compton scattering until escape from the atmosphere or absorption into the disk. The initial angular distribution of the photons is chosen for a scattering-dominated atmosphere (Chandrasekhar 1960). We employ the relativistic scattering formulae as well as the differential Klein-Nishina cross section to compute the scattering angle at each collision. In addition, the electrons are taken to have a relativistic Maxwellian distribution at the local temperature of the atmosphere.

To simplify the simulations the slab atmosphere is divided into approximately 600 bins (corresponding to radial annuli in the accretion disk), each of which is given constant disk and electron temperatures equal to the respective local temperatures at the center of the annulus. An equal number of photons enter each bin at the base of the atmosphere and scatter within a uniform temperature cloud. The escaped photons in each bin are appropriately weighted by a factor $T_0^4 r \Delta r$ and summed to create the final energy spectrum of the model. A similar integration over a finite radial range calculates the spectrum of the localized disk region which is hypothesized to produce the QPO photons. The ratio of the spectrum of the modulated photons to the total disk spectrum is then proportional to the fractional rms amplitude of the QPO as a function of energy.

We note that we do not include reflection off of the cold disk in these exploratory calculations. Rather, we assume that the absorbed photons will be thermalized by the disk and re-emitted with a blackbody distribution at the local disk temperature. That is, we treat the disk as a perfect blackbody. Photon number is not conserved in this process, but the total energy flux deposited into the disk is assumed to be re-emitted locally. Since this re-emitted distribution is the same as our initial input distribution, we can renormalize the escaped photon energy flux to include the total energy flux lost to absorption in the disk. We apply this rescaling of the escaped flux at each annular radius before we add the photons to compute the total energy spectrum for the model.

4. APPLICATION TO GRS 1915+105

Three known black hole candidates (BHCs) are each observed to display a high-frequency QPO (Morgan, Remillard, & Greiner 1997; Remillard et al. 1999a,b); two of these, a 67 Hz feature in GRS 1915+105 and a 300 Hz feature in GRO J1655-40, seem to remain stable in frequency despite appreciable changes in the source luminosity. The origin of these QPOs has been suggested to invoke effects of general relativity in the inner accretion disk since several time scales there can be associated with fast QPO at X-ray energies. Proposals for the QPO origins include: hot blobs at the innermost stable orbit (Morgan et al. 1997), frame-dragging effects (Merloni et al. 1999; Cui, Zhang, & Chen 1998; Markovic & Lamb 1998), inertial-acoustic instabilities (Milson & Taam 1997; Honna, Matsumoto, & Kato 1992), and diskoseismic oscillations (Nowak et al. 1997; Perez et al. 1997). To our knowledge the consistency of these models with the energy dependence of the QPO fractional amplitude has never been illustrated quantitatively.

To demonstrate the application of our tool we fit our numerically simulated energy spectra to data from RXTE observations of GRS 1915+105 taken during early 1996 when the 67 Hz QPO was particularly strong (1996 May 05; Morgan et al. 1997). In our analysis we limited the energy range of the Standard-2 PCA data from 2.5 to 25 keV and imposed a 1% systematic error over the entire energy range (Wilms et al. 1999). Spectral fitting was done using a grid of our four-parameter Monte Carlo spectra as an additive table model in XSPEC, version 10.00 (Arnaud 1996). The attenuation of radiation by the interstellar medium was taken into account using a second multiplicative model which employs the cross-sections of Balucinska-Church & McCammon (1992).

The Monte Carlo model spectrum which best fits the data is shown in Figure 3 with residuals plotted as the ratio of the data to the model. For comparison we also present the residuals of the best-fit spectrum from the phenomenological model of an absorbed disk-blackbody plus an additional blackbody component. Fit parameters for both models are listed in Table 1.

We note that the residuals for both models indicate a probable iron line near 6.4 keV. An ad hoc addition of such a component...
slightly improves the residuals from 5–10 keV ($\chi^2 = 0.39$) but does not significantly change the fit parameters for either model. Since the line is unimportant for both the overall flux and the resulting QPO energy dependence, we did not include it in our further modeling.

Using the best-fit parameters for the Monte Carlo model, we calculated the ratios of the modulated photon spectra to the total disk spectrum for three hypothesized regions of the 67 Hz QPO production. The resulting energy dependences of the QPO fractional amplitude are compared to the measurement of Morgan et al. (1997) in Figure 2. Each of the curves in Figure 2 has been normalized by a multiplicative factor to best describe the observational data. (This normalization factor corresponds to the fraction of photons emitted from the disk region which are modulated by the QPO mechanism.) Two of the curves are an acceptable fit to the data: one depicting QPO photons emitted from 6–7 $GM/c^2$ and one emitted from 7.5–8.5 $GM/c^2$. The third example, depicting a QPO produced in an outer disk region from 11–12 $GM/c^2$, does not reproduce the observation.

5. ANALYTIC APPROXIMATION

Wagoner & Silbergleit (1999) have developed an analytical formalism which considers Compton scattering in the slab model above for an assumed angular distribution of the photons (which is valid for the diffusion approximation and the two-stream approximation). Using the local approximation that gradients normal to the disk surface are dominant, they solve the Boltzmann equation governing the evolution of the radiation field under collisions (i.e., scattering events in the atmosphere). They invoke the Kompaneets approximation that the photon occupation number is assumed to be small.

Under these approximations the authors obtain an analytical expression for the photon energy flux (per unit energy, perpendicular to the disk surface) at any optical depth in the atmosphere. The solution involves only integrals over the input flux, which is a specified function of energy and may be a slowly varying function of $r$. For an input flux which is radially dependent, the emergent flux may be summed over radii if the physical thickness of the atmosphere is much less than the scale of radial gradients of the disk or cloud properties (a restriction which we note applies to our Monte Carlo model, as well).

Wagoner & Silbergleit apply their formalism to thin accretion disk atmospheres. Employing this application, we can compute the energy spectrum of QPO photons relative to the total energy spectrum of the disk and compare with the Monte Carlo application above. The parameters of the analytical model are the same as in our numerical work, namely $T_m$, $T_0$, $\tau$, and $r_c$. (We note that the formalism allows a more general application in which the inner radius of the disk exceeds $r_{ms}$ and in which the radial dependence of the electron temperature is arbitrary. The optical depth $\tau$ of the atmosphere may also be a slowly-varying function of $r$.) To complete the model one must specify the boundary condition at the top of the atmosphere ($\tau = 0$); the outer boundary condition was taken from standard scattering atmospheres (Chandrasekhar 1960).

The analytic approximation was employed within a proof-of-principle calculation to investigate the sensitivity of this tool. Over a range of parameters involving lower optical depths and higher cloud temperatures than the above fit to the 1996 May 05 observation of GRS 1915+105, we compared our Monte Carlo results to the analytical predictions. The common results were in good agreement. In particular, we obtained similar sensitivity to the location of the injected modulated photons.

6. SUMMARY

We have demonstrated a tool to locate the origin of QPO photons in accretion disk systems; the method uses the observed energy spectrum and the observed energy dependence.

![Figure 1: Spectral modeling of PCA data from RXTE observations of GRS 1915+105 on 1996 May 05. (a) Count rate spectrum and the best-fit Monte Carlo model spectrum. (b) Residuals from the Monte Carlo model shown as the ratio of the data to the model. (c) Residuals from the best-fit disk-blackbody plus blackbody model.](image1)

![Figure 2: Energy dependence of the 67 Hz QPO of GRS 1915+105 on 1996 May 05. Monte Carlo simulations are compared to data (5 points) from Morgan et al. (1997). Solid: same ratio for photons injected at 7.5–8.5 $GM/c^2$ ($n = 0.50$). Dashed: same ratio for photons injected at 11–12 $GM/c^2$ ($n = 0.34$).](image2)
of the QPO fractional amplitude to constrain the disk location in which the photon modulation may occur. Applying this technique to the BHC GRS 1915+105, we show that the functional energy dependence of the QPO amplitude constrains the origin of the QPO to be between the inner disk edge and just outside the maximum in the radial epicyclic frequency at $8GM/c^2$. This location is consistent with the models described in §4. From experience with our Monte Carlo and analytic models we can also suggest that observations of GRS 1915+105 which require hotter clouds to model comparatively harder spectra (e.g. 1996 June 12 from Morgan et al. 1997) may more precisely constrain the location of the QPO production.

The natural development of this tool will incorporate other geometries, as well as different temperature and density structures, to model the Comptonizing atmosphere. In addition, one must relax the assumption of a slowly-rotating central black hole. Although here we model the energy spectrum of GRS 1915+105 adequately with our simple choice of coronal construction, we do not fully constrain the structure of the atmosphere using relevant observations such as timing or coherence. The latter data should be used in conjunction with energy spectra to reveal the true nature of the electron clouds which might produce the high-energy photons seen in many BHC. The tool discussed in this Letter could then be a powerful indicator of the origin of QPOs in accretion disk systems.

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### Table 1

| Model          | $nH$ ($\times 10^{22}$) | $kT_{\text{bb}}$ (keV) | $kT_{\text{bb}}$ (keV) | $r_{\text{c}}$ ($GM/c^2$) | $kT_{\text{in}}$ (keV) | $kT$ (keV) | $\chi^2$/dof | $\chi^2_{\nu}$ |
|----------------|------------------------|------------------------|------------------------|---------------------------|------------------------|-----------|--------------|--------------|
| Monte Carlo    | 5.07$^{+0.08}_{-0.05}$ | 1.61$^{+0.01}_{-0.01}$ | 5.12$^{+0.08}_{-0.07}$ | 6.58$^{+0.27}_{-0.26}$   | 20.2$^{+0.98}_{-0.42}$ | ...       | ...         | 24.5/48      | 0.51         |
| diskbb + bbody | 4.57$^{+0.14}_{-0.14}$ | ...                    | ...                    | ...                       | ...                    | 1.65$^{+0.02}_{-0.02}$ | 2.64$^{+0.03}_{-0.02}$ | 46.8/49      | 0.96         |