A COMPTONIZATION MODEL FOR PHASE LAG VARIABILITY IN GRS 1915+105

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ABSTRACT

In this Letter we propose a simple thermal comptonization model to account for the observed properties of the phase lags associated to the “plateau” intervals of GRS 1915+105. By invoking a temperature stratification in a corona and assuming that the optical depth of the comptonizing region increases as the disk inner radius moves inward, we are able to reproduce both the observed colors and time lags in the continuum.

Subject headings: accretion, accretion disks — radiation mechanisms: non-thermal — stars: individual (GRS 1915+105) — X-rays: stars

1. INTRODUCTION

The galactic microquasar GRS 1915+105, discovered in 1992 by GRANAT (Castro-Tirado, Brandt & Lund 1992), is a transient source with an extremely wide variety of variability modes (Greiner et al. 1996; Belloni et al. 1997; Muno, Morgan & Remillard 1999). During the period 1996-1997 it has been extensively and repeatedly observed by the Rossi X-ray Timing Explorer (RXTE), alternating phases of dramatic variability to phases of remarkably regular behavior (Belloni et al. 2000).

GRS 1915+105 was the first galactic source to show superluminal radio expansion (Mirabel & Rodriguez 1994), usually interpreted in terms of emission from gas expanding at relativistic velocities. Measurements of this superluminal motion allow to estimate the source distance, which is in the range 6–12.5 kpc (Rodríguez & Mirabel 1999; Fender et al. 1999). Because of the high extinction along the line of sight, only a faint infrared counterpart has been discovered (Mirabel et al. 1994). As a consequence, neither the mass function nor the orbital period are known. The source is believed to host a black hole because it shows properties (variability and superluminal motion) very similar to the other known galactic microquasar, GRO 1655-40, for which a precise dynamical measurement yields \( M \sim 7M_\odot \) (Orosz & Bailyn 1997).

Quasi Periodic Oscillations (QPOs) have been observed in GRS 1915+105 in an incredibly large inter-val of frequencies, ranging from about 0.001 to 67 Hz (Morgan, Remillard & Greiner 1997; Chen, Swank & Taam 1997). In particular, in some observations a QPO with variable centroid frequency (\( \nu_{\text{QPO}} \sim 0.5–10 \text{ Hz} \)), whose value and root mean square amplitude correlate with the thermal flux, is detected (Markwardt, Swank & Taam 1999; Trudolyubov, Churazov & Gilfanov 1999).

The X-ray spectrum of GRS 1915+105 shows all the distinctive properties of other Galactic Black Hole Candidates (BHCs). A power-law tail with variable luminosity and slope is present at high energies, while a thermal component often dominates at low energies (Belloni et al. 1997; Muno, Morgan & Remillard 1999). A detailed spectral classification of the different states of GRS 1915+105 has been recently presented by Belloni et al. (2000). According to these authors, the variability of the X-ray emission is associated with the alternation of three basic states, called A, B and C (see also Markwardt, Swank & Taam 1999; Muno, Morgan & Remillard 1999). During states A and B, corresponding to relatively high and soft flux, a strong thermal disk component dominates the emission. In state C, the 3–25 keV flux is characterized by lower luminosity and harder X-ray colors, being dominated by a hard (\( \Gamma = 1.5–2.5 \)) power law with much softer (or even unobservable) thermal component. State C can last uninterruptedly, for a long time (weeks to months, the so called plateau intervals), in which case no soft component
is observed at all. State C is always associated with the 0.5–10 Hz QPO and a flat-top component in the Power Density Spectrum (Markward, Swank & Taam 1999; Trudolyubov, Churazov & Gilfanov 1999; Reig et al. 2000).

The analysis of a set of RXTE observations of GRS 1915+105 in this state showed that phase lags are present, both in the continuum and the QPO (Reig et al. 2000). The sign of the lag is correlated with QPO frequency, count rate and X-ray colors. The lag is positive (photons in the 5–13 keV band arrive later than those in the 2–5 keV band) when the spectrum is hard and the centroid of the 0.5–10 Hz QPO is below 2 Hz; it then becomes negative (soft photons are delayed) as the spectrum softens and the QPO centroid frequency increases above 2 Hz. The smooth correlations of the lags with colors suggests that a unique mechanism is driving the observed transition from positive to negative lags.

In this letter we propose a simple comptonization model to account for the observed properties of GRS 1915+105 in state C, which is outlined in § 2. In § 3 we report the main results obtained and compare them with observations. Finally, § 4 contains a short discussion of the implications of our results.

2. THE MODEL

No definite model for the accretion flow in GRS 1915+105 has been presented as yet. Here we consider a highly idealized scenario in which a Shakura-Sunyaev disk (Shakura & Sunyaev 1973) coexists with a hotter component. As suggested by Belloni et al. (1997), the main cause for the large-scale time variability of this source is the onset of a thermal-viscous instability which blows off the inner, radiation-pressure supported region of the disk. In particular, according to this scenario, the hard state corresponds to the replenishment by the disk of the previously evacuated region on a viscous timescale. Further support to this picture has been provided by numerical simulations (Szuszkiewicz & Miller 1997; 1998).

Fitting the observed spectra of BHCs in the hard state requires the presence, in addition to a standard disk, of a hot, less dense phase, formed e.g. by the debris of the puffed-up inner region or by the evaporation of the disk itself. The upscattering of soft disk photons by a hot cloud at $T \approx 10$ keV can account also for the positive lags of the continuum. In fact, Compton cloud models at constant temperature have been already proposed in connection with other sources which show (positive) time delays (Miyamoto et al. 1991; Vaughan et al. 1994; see also Poutanen 2000 for a review). Compton models suffer from the problem that soft photons cool down the cloud to the temperature of the impinging radiation, unless an efficient heating mechanism is at work. However, if cooling of ions is inefficient, like in advection-dominated flows, protons decouple from electrons and stay hot at a fraction of their virial temperature, $T_p(r) \approx \eta G M m_p/r$. The electron thermal balance is fixed by the competition between ion heating and Compton cooling. A simple estimate of the equilibrium electron temperature gives

$$T(r) \approx 10 (c^2 r_{in}/GM)^{2/5}(1 - r_{in}/r)^{-2/5} \text{keV} \quad (1)$$

for a scattering depth $\gg 1$, $\eta = 0.01$, and $L_{soft} \propto (1/r_{in} - 1/r)$. As expected (see Poutanen 2000), the cloud temperature diminishes as the disk rim moves in and $L_{soft}$ increases, but the dependence is weak. In an ion-heated corona the temperature is larger at smaller radii because $L_{soft}$ decreases with $r$ so that less photons are available to cool the inner part of the cloud.

A non-homogeneous Compton cloud model may indeed explain the positive/negative lags and the decrease in the hard color observed in the state C of GRS 1915+105, provided that the corona becomes denser as the disk extends inwards. The density may increase in time if a cloud of fixed mass contracts as the result of angular momentum losses caused by viscous and/or radiation stresses. In order to illustrate the basic idea of the model, we sketch the corona as formed by two regions (referred to as “warm” and “hot”), each at uniform density and temperature, $T_W$ and $T_H$, with $T_H > T_W$ (see Figure 1). The scattering depths are $\tau_W$ and $\tau_H$, $\tau_H > \tau_W$. When the density of the corona is low, soft photons get preferentially scattered in the inner part of the corona which has $\tau_H \approx 1$ (while $\tau_W \approx 1$), gaining energy and producing a positive lag. As density increases, the Compton $y$-parameter of the corona exceeds unity below a certain radius $r_{sc}$. Photons emitted by the inner part of the disk undergo repeated scatterings with the hot electrons and start to fill the Wien peak at $T_H$. The spectrum emitted by the disk plus the hot, dense part of the corona is therefore the superposition of a multitemperature blackbody and a Bose-Einstein distribution at $T_W$; the latter has the same number of photons originally emitted by the disk in the region $r_{in} < r \approx r_{sc}$. These photons have still to traverse the warm part of the corona before escaping to infinity. In doing so, they are downscattered and this produces the negative lag and the observed spectrum. A somehow similar geometry (a standard disk with variable radius and a hotter, comptonizing cloud), although in a different context, has been successfully invoked to explain the spectral properties of Nova Muscae 1991 (e.g. Misra & Melia 1997; Esin, McClintock & Narayan 1997).
In the next section we show that quantitative estimates, based on this simple picture, are indeed in agreement with the observed colors and lags for reasonable values of the parameters. In our model the inner radius changes only by a factor \( \sim 3 \), so, for the sake of simplicity, in the following we neglect the small (\( \sim 1.5 \), see eq. [1]) change of \( T \) with \( r_{in} \).

3. NUMERICAL ESTIMATES

The calculation of the emerging spectrum proceeds in two steps and follows the standard procedure discussed by Sunyaev & Titarchuk (1980). First, we compute the time-dependent comptonized spectrum for a given seed photon distribution by solving the Kompaneets equation in a semi-infinite homogeneous medium and then use an escape probability algorithm to obtain the time evolution of the spectrum emerging from a medium of finite depth. We introduce a dimensionless time \( u = (n_e \sigma_T \theta^2) t \) and energy \( x = hv/kT \), where \( n_e \) is the electron density, \( \sigma_T \) the Thomson cross-section and \( \theta = kT/m_e c^2 \). In the following all lengths are expressed in units of \( GM/c^2 \). The photon occupation number \( n(u, x) \) is the solution of the Kompaneets equation with an appropriate initial condition \( n(0,x) \). For \( r_{in} > r_{sc} \) the initial photon occupation number is that of a multitemperature blackbody (calculated including GR and hardening effects, e.g. Novikov & Thorne 1973; Shimura & Takahara 1995) truncated at \( r_{in} \), whereas, for \( r_{in} < r_{sc} \), it corresponds to the superposition of a Bose-Einstein distribution at \( T_H \) and a multitemperature blackbody truncated at \( r_{sc} \).

Since in our model the long-term evolution corresponds to a variation of the inner edge of the disk, the Kompaneets equation has been solved numerically for a sequence of values of \( r_{in} \). Once \( n(u,x) \) has been evaluated, the time evolution of the escaping photons is given by

\[
N(u,x) = x^2 n(u,x) P(u,\tau) \tag{2}
\]

where \( N \) is proportional to the count rate and \( P(u,\tau) \) is the escape probability distribution. The explicit form of \( P(u,\tau) \) depends on the geometry (Sunyaev & Titarchuk 1980). In our calculations we have used a weighted sum of the expressions for a spherical cloud with either a central or a diffused photon source.

The total count is proportional to the convolution

\[
F(x) = \int_0^\infty x^2 n(u,x) P(u,\tau) \, du . \tag{3}
\]

We note that eq. (3) gives exactly the spectrum produced by a stationary source of photons. Therefore it will be used to compute the hardness ratios on time intervals substantially larger than typical variability timescales in the continuum. On the other hand, if one is interested in following the time evolution of the spectrum over timescales \( \sim 1/\nu QPO \) the relevant quantity to consider is \( N(u,x) \).

To reproduce the observed time evolution of the color in a given energy band we have convolved \( N(u,x) \) with the interstellar absorption and with the detector response function

\[
C(E_1 - E_2) \propto \int_{E_1}^{E_2} N(u,x) \exp \left[ -N_H \sigma(x) A(x) \right] dx \tag{4}
\]

where \( N_H \) is the column density. The lags in the continuum are computed comparing the time evolution of the soft and hard colors, \( C(2-5) \) and \( C(5-13) \), as obtained from eq. (4). The hardness ratios HR1 and HR2, defined as \( C(5-13)/C(2-5) \) and \( C(13-60)/C(2-5) \), are calculated again starting from eq. (4) but this time replacing \( N(u,x) \) with \( F(x) \).

The calculations presented here have been obtained for \( T_H = 15 \text{ keV}, T_W = 1.5 \text{ keV} \) and \( r_{sc} = 20 \); the black hole mass and angular momentum are \( M = 6M_\odot \) and \( a = 0.1M \). The model with \( r_{in} = 16 \) corresponds to the usual picture in which a hot corona (\( T = T_H \)) of moderate depth (\( \tau = \tau_H \sim 3 \)) upscatters the soft photons produced by the disk; under these conditions the energy exchange in the warm region can be reasonably assumed to be negligible. The opposite situation is represented by the model with \( r_{in} = 6 \). Now the disk inner region lies entirely within the hot part of the corona which, because of the increase in the density, has \( \tau_H \geq 100 \). Escaping photons are then reprocessed in the outer, warm part of the corona (\( T = T_W, \tau = \tau_W \sim 10 \)). Intermediate cases are more difficult to model in the present framework, because photons scatter in both regions and this would require a treatment of comptonization in a non-uniform medium. To avoid undue complications, at this stage we assume that the effects of a temperature profile can be roughly described in terms of an “effective” temperature \( T, T_W < T < T_H \). For these models \( T \) and \( \tau \) were chosen in such a way to maintain \( y \sim 1 \).

Our results are illustrated in Figure 2. As shown in Figure 2a, the observed hardness ratios are quite well reproduced by the model for a value of the column density, \( N_H = 2 \times 10^{22} \text{ cm}^{-2} \), consistent with observations (Belloni et al. 2000). When the inner edge of the disk is far out, the spectrum is a power-law produced by thermal comptonization of soft disk photons. As \( r_{in} \) decreases, downscattering becomes progressively more important with respect to upscattering in the hot corona, the spectrum softens and, at the same time, the phase lag of the continuum decreases. Eventually, systematic downscattering dom-
inates and soft (2–5 keV) photons, which underwent more scatterings, escape later than hard (5–13 keV) photons, causing an inversion in the sign of the lag. Figures 2b and 2c show the lag of the continuum as a function of HR1 and QPO frequency (the scattering of the computed points is partially due to the poor sampling of the parameter space). Time lags have been computed assuming that the typical size of the comptonizing corona varies with time in accordance with the comptonization temperature. The contraction of the corona (a factor ~ 20) required to reproduce the largest/smallest lags implies an increase in the density (ρ ∝ R−3 at constant coronal mass) consistent with the assumed ratio of the scattering depths, τH(ri = 6)/τH(ri = 16) ~ 100. The smallest value of the inner disk radius required by the model, ri ≃ 6M, is consistent with the assumed value a/M = 0.1. If the black hole is rapidly rotating, as claimed by Zhang, Cui & Chen (1997) and Cui, Zhang & Chen (1998), then in low luminosity state C the disk does not reach the innermost stable circular orbit.

A complete discussion of the behaviour of GRS 1915+105 in states A and B is outside the scope of the present investigation. Here, we simply mention that models with high coronal optical depth but hard-photon starved (because, e.g., of the final collapse of the innermost, denser part of the corona) have hardness ratios in agreement with those observed in states A and B. Although no QPO has been observed in these states as yet, the positive detection of time lags correlated with colors in states A and B may lend further support to the present Compton model.

Very recently, complex phase lag behavior in XTE J1550-564 has been reported by Cui, Zhang & Chen (2000). The power spectra are very similar to those in Reig et al. (2000). However, the QPO phase-lag dependence is different. The fundamental/first harmonic shows a negative/zero lag, increasing in magnitude as the spectrum softens. In the light of the higher complexity of the timing properties of XTE J1550-564, any attempt to extend the present model to this source is premature.

REFERENCES


In this Letter we have shown that a simple Compton model can account for the main observational properties of GRS 1915+105 in state C. In particular, the fundamental correlations (color–color, lag–color and lag–QPO frequency) are successfully reproduced for a reasonable choice of the model parameters. Although we have adopted here a quite definite picture for the accretion flow, it is important to stress that the basic results are largely independent of the specific choice for the geometry. The decrease of the lag in the continuum and the softening of the spectrum as the disk fills in are simply a consequence of the increase of the coronal depth and of the decrease of the temperature where radiation scatters before escaping. Thus, only three main ingredients are required to account for the observed correlations within the framework of a simple thermal comptonization model: a non-isothermal corona of varying optical depth, a truncated standard disk and a source of more energetic (≈ 10 keV) primary photons at small radii. Further assumptions (like the variable size of the corona and the existence of an “effective” comptonization temperature) are introduced only to match the observed values. It should be noted, however, that other geometrical settings for the time-varying accretion flow may work equally well.

On the other hand, albeit not directly supported by hydrodynamics computations, the flow structure adopted here exhibits a certain degree of consistency in the way in which the QPO frequency and the coro-

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natural optical depth vary with inner disk radius. In fact, without entering into the mechanism that originates the observed QPO, we have assumed that it is somehow produced at the inner edge of the disk and that its frequency varies with ri. It is interesting to note that the relation between νQPO and ri derived in § 3 (eq. [5]) is similar to that found by Di Matteo & Psaltis (1999) combining the empirical relation of Psaltis, Belloni & van der Klis (1999) with the upper bound provided by the keplerian orbital frequency. We stress, however, that our result has been obtained in an independent way and is a direct consequence of the values of the inner disk radius needed to match the observed colors and time lags. The contraction of the corona (a factor ~ 20) required to reproduce the largest/smallest lags implies an increase in the density (ρ ∝ R−3 at constant coronal mass) consistent with the assumed ratio of the scattering depths, τH(ri = 6)/τH(ri = 16) ~ 100. The smallest value of the inner disk radius required by the model, ri ≃ 6M, is consistent with the assumed value a/M = 0.1. If the black hole is rapidly rotating, as claimed by Zhang, Cui & Chen (1997) and Cui, Zhang & Chen (1998), then in low luminosity state C the disk does not reach the innermost stable circular orbit.

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**Fig. 1.**—A schematic view of the accretion flow in the central region of GRS 1915+105 in state C. The three panels illustrate the evolution as the disk rim moves closer to the hole (from left to right). Temperature increases from black to white.

**Fig. 2.**—a) color-color diagram for the model discussed in the text (filled diamonds) compared with observations (open circles); b) predicted and observed phase lags of the continuum versus HR1; c) predicted and observed phase lags of the continuum versus QPO frequency. Each model is labeled by the value of $r_{in}$ in units of $GM/c^2$. 