RADIATION PRESSURE INSTABILITY AS A VARIABILITY MECHANISM IN THE MICROQUasar GRS 1915+105

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ABSTRACT

The physical mechanism responsible for the high viscosity in accretion disks is still under debate. The parameterization of the viscous stress as $\alpha P$ proved to be a successful representation of this mechanism in the outer parts of the disk, explaining the dwarf novae and X-ray novae outbursts as being due to ionization instability. We show that this parameterization can also be adopted in the innermost part of the disk where the adoption of the $\alpha$-viscosity law implies the presence of the instability in the radiation pressure–dominated region. We study the time evolution of such disks. We show that the time-dependent behavior of GRS 1915+105 can be well reproduced if the $\alpha$-viscosity disk model is calculated accurately (with proper numerical coefficients in vertically averaged equations and with advection included) and if the model is supplemented with (1) a moderate corona dissipating 50% of energy and (2) a jet carrying a luminosity-dependent fraction of energy. These necessary modifications in the form of the presence of a corona and a jet are well justified observationally. The model predicts outbursts at a luminosity larger than $0.16M_{\odot}\dot{M}$ as required, and correct outburst timescales and amplitudes, including the effect of an increasing outburst timescale with mean luminosity. This result strongly suggests also that the $\alpha$-viscosity law is a good description of the actual mechanism responsible for angular momentum transfer in the innermost, radiation pressure–dominated part of the disk around a black hole.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — instabilities — stars: individual (GRS 1915+105)

1. INTRODUCTION

A standard, geometrically thin accretion disk (Shakura & Sunyaev 1973) is known to be unstable in the innermost, radiation pressure–dominated regions (Lightman & Eardley 1974; Pringle, Rees, & Pacholczyk 1974). The presence of this instability is due to an assumption that the viscous torque is proportional to the total (gas + radiation) pressure. Since our understanding of the nature of viscosity in a disk is poor (for a review, see Papaloizou & Lin 1995), we can explore the viscosity mechanism indirectly, through modeling the consequences of the radiation pressure instability and comparing them with the observed variability of X-ray sources.

On the theoretical side, the basic description of stationary solutions was completed by Abramowicz et al. (1988), who found that radial advection stabilizes the disk at high accretion rates so that a time-dependent behavior was expected only for intermediate accretion rates. The disk evolution was first computed by Honma, Matsumoto, & Kato (1991), and Szuszkiewicz & Miller (1998) presented computations of several consecutive outbursts, thus confirming a limit-cycle behavior of the disk.

On the observational side, a perfect candidate has been found to study the details of radiation pressure instability. This is the X-ray source GRS 1915+105 that was discovered using the Granat Observatory (Castro-Tirado, Brandt, & Lund 1992) and that was extensively observed by the Rossi X-Ray Timing Explorer (RXTE; Belloni et al. 1997a, 1997b). The source exhibits a superluminal jet (Mirabel & Rodríguez 1994). During outbursts, its X-ray luminosity is dominated by a disklke component (Belloni et al 1997a), and therefore the observed variability in this state should reflect the time behavior of the disk. The variations are well modeled phenomenologically by periodic changes of the disk inner radius (e.g., Feroci et al. 1999). The scenario, in which the radiation pressure instability is actually responsible for these variations, was outlined by Belloni et al. (1997c). The duration of the hard spectral state episodes in the disk-dominated epochs was recently identified with the viscous timescale of a standard, radiation pressure–dominated disk (Trudolyubov, Churazov, & Gilfanov 1999).

However, the time evolution computations of Honma et al. (1991) and Szuszkiewicz & Miller (1998) that are based on radiation pressure instability strongly overpredict the amplitude of the outburst of GRS 1915+105. Therefore, Nayakshin, Rapponport, & Melia (2000) suggested that the standard viscosity law does not apply, and they successfully reproduced the overall shape of the GRS 1915+105 RXTE light curve under an assumption of the viscosity law of Taam, Chen, & Swank (1997). In order to reproduce the observed minimum luminosity required for outburst behavior, they also had to assume that the disk dissipates only 10% of the energy, with the remaining energy dissipated in a hot corona, which is not supported by observations.

In this Letter, we apply the standard viscosity assumption, and nevertheless we still successfully reproduce the RXTE light curve of GRS 1915+105. The key elements of our model, in comparison with Honma et al. (1991) and Szuszkiewicz & Miller (1998), are (1) the presence of the outflow in the form of a jet (modeled after Nayakshin et al. 2000), (2) the use of the appropriate coefficients in vertically averaged equations determined from the disk’s vertical structure, and (3) the pres-
ence of a moderately strong corona dissipating 50% of the energy.

2. METHOD

2.1. Assumptions

We study the time-dependent structure of a Keplerian vertically averaged accretion disk. We use a standard viscosity prescription; i.e., we assume that the viscous stress tensor is proportional to the total pressure, \( P (\tau_{\nu} = -\alpha P) \).

The angular momentum distribution of the disk material is approximated as Keplerian, and so we neglect the problem of the transonic character of the flow that is close to the marginally stable orbit, which was studied by Honma et al. (1991) and Suszczewicz & Miller (1998). Instead, we pay much more attention to the various disk cooling mechanisms.

We assume that the heat generated within the disk at any radius is either stored temporarily within this radius or removed by (1) radiation, (2) advection, or (3) a jet. Because the spectral observations show the presence of a hard X-ray tail, we also assume the existence of a hot corona.

The radiative cooling of the disk is calculated by assuming that the disk is optically thick and that it radiates as a blackbody.

The fraction of energy carried by advection is determined by the local accretion rate at a given moment and radius, measured in units of the Eddington accretion rate:

\[
\frac{\dot{m}}{\dot{m}_{\text{Edd}}} = \frac{4\pi G M m_{\text{pl}}}{c^{3} \eta} = \frac{4\pi G M m_{\text{pl}}}{c^{3} \eta}.
\]

The assumed efficiency of accretion is \( \eta = 1/16 \) since it results from the pseudo-Newtonian approximation to the disk accretion.

In our model, this cooling mechanism is included in the energy balance, which is opposite the model of Nayakshin et al. (2000) in which the jet was only used as an energy channel carrying a fraction of the energy dissipated in the corona. The fraction of the energy dissipated in the corona is a free parameter of the model, and in the present model, we assume that it takes a constant value, \( f_{\text{cor}} = 0.5 \), independent from time and radius.

The time evolution of the disk is governed by two equations, i.e., the energy balance given in the following form:

\[
\Sigma T \frac{\partial \Sigma}{\partial t} = F_{\text{gen}} - F_{\text{rad}} - F_{\text{adv}} - F_{\text{jet}} - F_{\text{cor}},
\]

and the standard equation describing the time evolution of the disk surface density:

\[
\frac{\partial \Sigma}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( 3r^{1/2} \frac{\partial}{\partial r} \left( r^{1/2} \nu \Sigma \right) \right),
\]

where the cooling by the jet and corona is defined as

\[
f_{\text{jet}} = \frac{F_{\text{jet}}}{F_{\text{rad}} + F_{\text{adv}} + F_{\text{jet}}} \quad \text{and} \quad f_{\text{cor}} = \frac{F_{\text{cor}}}{F_{\text{rad}} + F_{\text{adv}} + F_{\text{jet}} + F_{\text{cor}}},
\]

The determination of the algebraic relation between the quantities in equations (3) and (4) results from the continuity equation, the hydrostatic equilibrium, and the radiative transfer. It involves the determination of dimensionless coefficients, which results from the replacement of the disk vertical structure with vertically averaged (or equatorial) quantities (e.g., Abramowicz et al. 1988; Honma et al. 1991).

We determine those coefficients from the study of the vertical structure of a stationary disk at 10 \( r \) (see, e.g., Dörer et al. 1996). Apart from standard ingredients, our stationary disk model included the effect of radial advection, energy transport by convection, and appropriate bound-free opacities. The numerical code used for the computations was developed from the version by Pojmański (1986) and subsequently modified by Różeńska et al. (1999). The coefficients, as defined by Muchotrzeb & Paczyński (1982) and Abramowicz et al. (1988), are \( B_{1} = 0.8 \), \( B_{3} = 5.0 \), and \( B_{4} = 6.0 \), while the above authors used \( B_{1} = 0.67 \) and \( B_{3} = B_{4} = 6.0 \), and Honma et al. (1991) used \( B_{1} = 1.0 \), \( B_{3} = 16.0 \), and \( B_{4} = 8.0 \).
The importance of the model ingredients is illustrated by the stability curve of a stationary model calculated at 10R_{\text{schw}} for a 10 M_\odot black hole mass and a viscosity parameter \( \alpha = 0.01 \) (see Fig. 1). The triangles in Figure 1 were obtained from the solution of the disk vertical structure; the dashed line is the stability curve obtained from the vertically averaged disk equations (with appropriate coefficients). In these two cases, the disk corona and jet were neglected (\( A = 0 \) and \( f_{\text{cor}} = 0 \)). The dotted line shows a modification of the stability curve by the corona (\( f_{\text{cor}} = 0.5 \)). The solid line shows the effect of the jet (\( A = 0.05 \)).

On the same plot, the circles show the stability curve calculated in a similar manner to the method adopted by Nayakshin et al. (2000); i.e., we computed the disk surface density from the vertically averaged disk structure as specified in that paper, but we assumed the standard viscosity law. For the Nayakshin et al. model, the instability occurs for accretion rates as low as \( \dot{m} \sim 0.03 \). Therefore, in order to stabilize the disk at low \( \dot{m} \), the authors had to postulate a strong corona. In our model, we expect the instability to appear for accretion rates higher than \( \dot{m} \sim 0.1 \) at that radius and even higher than \( \dot{m} \sim 0.2 \) if half of the gravitational energy is dissipated in the corona (\( f_{\text{cor}} = 0.5 \)).

### 2.2. Time Evolution and Model Parameters

We use the time evolution code that was originally developed and described in detail by Smak (1984) for the study of cataclysmic variables and that was modified by Siemiginowska, Czerny, & Kostyunin (1996) in the context of the ionization instability in the active galactic nucleus (see also Hameury et al. 1998). We adopt the mass supply \( \dot{m}_0 \) to the inner part of the disk as a model parameter, and we follow the time evolution of the disk under the radiation pressure instability using thermal and viscous timescales, as studied by Szuszkiewicz & Miller (1998). The complete model is given by the mass supply rate \( \dot{m}_0 \), the viscosity parameter \( \alpha \), the jet efficiency factor \( A \) (relating the fraction of energy carried by the jet to the local temporary accretion rate), and the (fixed) fraction of energy dissipated in the corona \( f_{\text{cor}} \).

### 3. RESULTS

We calculate the time evolution of the disk for a set of parameters that are adequate to explain the timescales and the amplitudes of the typical outbursts observed in GRS 1915+105. In the following, we assume that the black hole mass is equal to \( M = 10 M_\odot \) (the estimated mass of the microquasar ranges from 7 to 33 M_\odot), the viscosity parameter \( \alpha = 0.01 \) (as used by Nayakshin et al. 2000 on the standard branch), \( f_{\text{cor}} = 0.5 \) (a moderate corona), and \( A = 0.05 \) (a mildly strong jet efficiency).

The instability can occur only above a certain accretion rate limit for a given mass and viscosity. For our choice of parameters, the disk is stable when the accretion rate \( \dot{m}_0 \) is smaller than 0.16. For accretion rates above this limit, the disk exhibits strong and regular outbursts.

The amplitude of the global outburst depends mostly on the shape of the stability curve in the innermost part of the disk; this will constrain the jet efficiency \( A \). The duration of the limit cycle, on the other hand, is basically determined by the viscous timescale at the outer radius of the instability zone in a stationary model, so it scales with the choice of the viscosity parameter \( \alpha \).

In Figure 2, we show four light curves calculated for four values of the external accretion rate. Other parameters were kept the same. The plotted light curves represent the bolometric luminosity of the disk. However, to some extent, they may be directly compared with the observed light curves expressed in units of counts per second since the count rate in the RXTE is strongly dominated by the soft energy band, which is determined mostly by the disk luminosity. The outbursts are almost periodic, but their overall shape is significantly influenced by the mass supply rate. When \( \dot{m}_0 \) is only slightly larger than the minimum value required for the instability to operate, the outbursts last only \( \sim 100 \) s, and the separation between them is...
relatively long. With an increase of $\dot{m}_\text{in}$, the duration of the bursts increases up to $\sim 1000$ s, although the amplitude does not change strongly. Similar results were obtained by Nayakshin et al. (2000). Although their approach to the description of the disk structure was different from ours, it led to a similar stability curve and therefore similar outburst properties.

By comparing our model with the GRS 1915+105 behavior, we conclude that the observed shape of the microquasar’s light curves can be obtained by varying the mass supply rate. The observed outburst’s amplitude constrains the jet efficiency. The energy carried away in the jet varies during the cycle: it is negligible at low luminosity but can reach $\sim 15\%$--$20\%$ during the outburst, for an assumed $A = 0.05$. The jet losses thus provide a more efficient mechanism for stabilizing the disk than does the advection, and they ensure that the luminosity of the source during the outburst does not exceed the Eddington value.

The viscosity parameter $\alpha$ does not influence the shape of the stability curve, and therefore the amplitude of the outburst remains the same as long as $\alpha$ is the same on the upper and lower branches. The change of $\alpha$ in this case results in the horizontal shift of the entire $\dot{m}-\Sigma$ curve. However, this strongly affects the surface density and the viscous timescale, and so for small $\alpha$, the surface density is higher and the viscous timescale is longer. The adopted value well represents the observed timescales in the microquasar.

4. DISCUSSION

We show that a physically viable instability that is due to the radiation pressure in a standard disk model can well represent the time-dependent behavior of GRS 1915+105 if the advection and the presence of a moderate corona ($f_{\text{cor}} = 0.5$) and a jet are included in the model. The mechanism operates for accretion rates above $\dot{m}_\text{in} \sim 0.16$, which is in agreement with the observations of GRS 1915+105—the source does not exhibit any outbursts if the mean luminosity temporarily drops below $2.1 \times 10^{38}$ ergs s$^{-1}$. The viscosity coefficient on the order of 0.01 is appropriate for modeling the typical outburst duration as a function of the mass supply to the innermost part of accretion disk. The presence of the jet is necessary to explain the observed amplitude of the outburst since without the jet, the light-curve variations are too large (by a factor of $\sim 30$). The roles of the advection and the jet in the parameterization presented are similar, but for the required value of the jet efficiency, the jet losses dominate and the effect of advection is never strong.

We conclude that the parameterization of the viscous stress, which is proportional to the total pressure, well represents the true viscous stress properties and that the radiation pressure instability is a promising model of the basic instability mechanism underlying the observed variability of this microquasar. The energy losses due to the jet are an essential ingredient of such a model. Models based on a modified viscosity law may allow for a much lower jet efficiency. Observational constraints on the amount of energy carried by the jet will allow us to distinguish between the two possibilities.

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