ISAS-RN-654-C
Jun 1998

AUG 24 1998

ISAS-RN-654-C

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ARE THE X-RAYS COMING FROM THE INSIDE OF THE ACCRETION DISK OF THE BLACK HOLE ?

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1. Introduction

1.1. WHAT IS THE EVIDENCE FOR BLACK HOLES ?

Previous X-ray observations have revealed that about 20 X-ray stars show common X-ray properties distinct from neutron star systems and white dwarf systems. The central masses of about 10 of them were estimated from optical observations, and turned out to be in excess of the theoretical upper limit of the mass of a neuron star (e.g., Tanaka *et al.*, 1996).

Such massive X-ray stars commonly exhibit aperiodic rapid time variations in X-ray intensity on time scales of milliseconds, implying that the X-ray emission region is very compact, say 10^7 cm. The estimated masses and the compactness of the emission region strongly suggest that the X-ray stars are black holes. Those stars are, however, still called black hole candidates (BHCs) because we have not yet observed any property closely tied to black holes themselves.

Estimating the mass of invisible objects is the great first step to finding black holes as discussed by other authors in this volume. However, it does not tell us that the black holes we imagine really exist in the central regions of those objects. Since the black holes we imagine do not emit light at all, we cannot confirm their existence directly. Fortunately, relativistic theory also predicts that, on the inside of the innermost stable orbit, matter almost free-falls onto black holes and little energy is released. Thus, its confirmation will be the next step. In this sense, X-ray/γ-ray observations are of great importance because such high energy photons are thought to be emitted in the vicinity of the central object.

1.2. EVIDENCE FOR ACCRETION DISKS

Extensive X-ray observations have demonstrated the existence of accretion disks around massive objects. Ultrasoft spectral components have been observed in many BHCs, usually when the X-ray intensity is relatively high. The spectra are well represented by a multicolor disk blackbody model, which is a simple optically thick accretion disk model with the innermost radius r_{in} and the radial temperature dependence of $T \propto r^{-3/4}$, where r is the distance from the center and T is the temperature at r (Makishima *et al.*, 1984). Most of the observations showed that r_{in} was almost *constant* even though X-ray flux of this component changed by a factor of more than 10, implying that r_{in} is the innermost stable orbit (e.g., Kitamoto, 1998).

The observed temperature and luminosity basically enable us to estimate the size of the innermost radius, which can be connected with the mass of the central object provided that $r_{in} = 3r_s$, where r_s is the Schwarzschild radius. The masses of BHCs, estimated in such a way, are systematically larger than those of low-mass X-ray binaries (e.g., Inoue, 1991).

ASCA detected a broad iron $K\alpha$ line from some AGNs. The line profiles imply that the emission region extends over $3r_s$ (Tanaka *et al.*, 1995; Nandra *et al.*, 1997). This can also be evidence for the accretion disk, though the disk structure has not been understood. However, neither of these observations give information on the inside of the innermost stable orbit.

1.3. X-RAY TIME VARIATIONS

BHCs show aperiodic time variations, which is one of their properties which is distinct from other systems. The nature of the time variations was, however, not well understood because the Fourier analyses of the time variations, which had long been utilized to evaluate the variations, did not give any useful information on the origin of the time variations. The time variations must have important information not only on the radiative process but also on the dynamical process. Therefore, they may contain a clue connecting the observed properties to the black holes.

Useful physical information obtained from results of previous timing analyses was the shortest time scale, $\sim$ 3 ms, providing the maximum size of the emission region (Meekins *et al.*, 1984), and the longest time scale, $\sim$ 10 sec, suggesting that so-called X-ray shots arise from the mass accretion (Rothschild *et al.*, 1974). The superposition technique is, however, a powerful method to obtain average profiles of the shots and their spectra without any ad hoc assumptions in contrast with the shot-noise models (Lochner *et al.*, 1991 and references theirin). Obtained results can be closely related with the physical condition near the innermost radius and inside it. The results will be described next, focusing on the evidence for black holes.

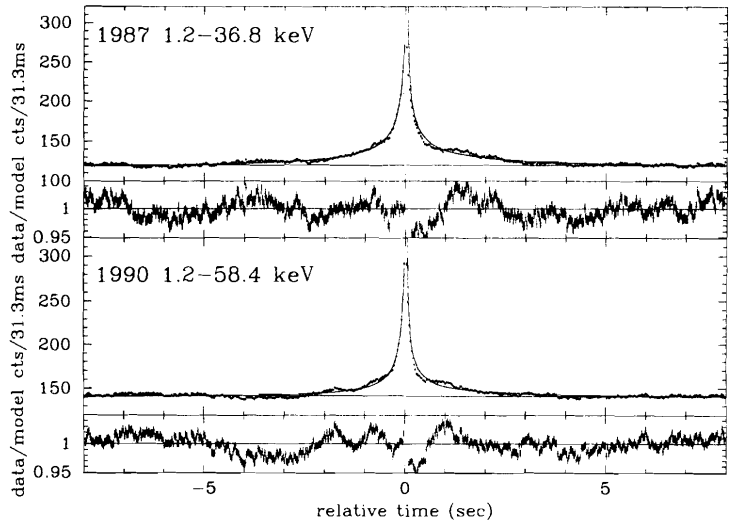

Figure 1. Average shot profiles of Cyg X-1 in 1987 and 1990 observations and the best fitting fractal function models (solid lines). Their ratios are also shown.

2. Data and Analyses

The superposition technique was first introduced in order to investigate average properties of the shots of Cyg X-1 using *Ginga* data (Negoro *et al.*, 1994). An average profile is obtained by superposing a number of shots with peak counts larger than a certain factor (typically 1.5-2.5) of the local mean number of counts. In superposing the shots, the events are aligned with their peak-bin positions in all the energy bands, not in each energy band (see Negoro, 1995a in detail).

All the results described here were obtained using *Ginga* data of Cyg X-1, GX 339-4, GS 2023+338 and GS 1124-68 in the low state (Negoro, 1997). In those data, selected shot events are statistically significant, but the peak-bin positions suffer from the statistical count fluctuations. Numerical simulations show that the accuracy of the alignment depends on the count rate, being 20–60 ms in the data used here.

3. Results

3.1. SHOT PROPERTIES

Figure 1 shows average shot profiles of Cyg X-1 in 1987 and 1990 observations (Negoro, 1995a). The other BHCs also show similar shot profiles (Negoro, 1997). Both the rise and decay profiles can be roughly represented by

the following empirical functions. One is a sum of two exponential functions with time constants of about 0.1 sec and about 1 sec. A single exponential function gives poor fits to both the profiles due to long wings extending for more than 2 sec before and after the sharp peaks. The other is a *fractal* function proportional to $1/(\tau + |t|)^{\alpha}$ where t is the relative time from the maximum intensity time and τ and α are free parameters.

Due to the slightly asymmetric profiles, in most cases, the fractal function gives better fits to the rise profiles than to the decay profiles (see ratios in Fig. 1). τ and α obtained from fits to the rise profiles are 0.07–0.8 and 0.8–1.5, respectively. The obtained fitting parameters are different not only in different sources but also in the same source on different occasions (see Fig. 1), indicating that the shot profiles are not peculiar to each source. However, more detailed analyses show that the rise profiles do not change on time scales of hours or less, at least in Cyg X-1. The shot profiles also do not depend on the peak intensities, especially in the rise phases. Note that this independence, however, does not imply that all the shots have the completely same profile in the short time scales. Some selected shots have a similar profile to the average one, but others do not. The obtained profiles only present *average* profiles in some period.

Energy spectra of the shots give further information. The *Ginga* data used here have 12 or 48 spectral bins in the 1.2–37(58) keV band. All the sources show similar spectral evolution during the shots. The shots have softer spectra than the time averaged spectra, especially in the rise phases. The spectra suddenly harden at the peak intensities. The durations of the hardenings are 20–60 ms, which suffers from the mis-alignment in superposing shots as described before. Simulations show that a possibility of change in less than the minimum time resolution (7.8 ms) can not be ruled out. After the peak intensities, the spectra continue to be harder for 0.2-0.3 sec. After that, transient, slight softening is recognized in some sources.

3.2. COMPARISON WITH RESULTS OF FOURIER ANALYSES

Observed structures in power spectral densities (PSDs) and hard X-ray time lags below a few Hz are consistent with the above characteristics of the shots (Negoro, 1995a; Negoro, 1997). The PSDs of BHCs in the low state have two knees around 0.01–0.1 Hz and 1 Hz (Miyamoto *et al.*, 1992). The two knees reflect the shot profiles represented by the two time constants. The 'double-peaked' phase (time) lags are due to the gradual spectral hardening after the peak intensity and the following changes.

Structures above a few Hz in the PSDs and the time lags, however, can not be explained by the shots. This is not due to the fact that superposing

a number of shots smears rapid (< 20–60 ms) time variations. Normalized PSDs showing the relative amplitudes of the variations indicate that, at those high frequencies, in contrast with the low frequencies, normalized PSDs in the low energy bands have lower values than those in the high energy bands, suggesting another high frequency component has a hard energy spectrum.

4. Discussion

4.1. ORIGIN OF THE TIME VARIATIONS AND RELATIONSHIP WITH BLACK HOLES

The gradual increase in intensity and the independence of the shot profiles from the peak intensities rule out shot occurrence models based on *local* disk instabilities and/or magnetic field reconnections. Because such models showed much shorter time scales (≤ 0.1 sec) for fluctuations. The duration and the magnitude of a fluctuation also depend on the radius where it occurs (e.g., Piran, 1978; Galeeve *et al.*, 1979).

The general properties of the shots can be explained by a model in which the shots arise from density fluctuations of accreting matter drifting onto a black hole. If the radial velocity of a clump of accreting matter v_r ($= dr/dt$) and X-ray emission from it $l(r)$ are expressed by powers of the radial distance r such as $v_r = -C_1 r^{-\lambda}$ and $l = C_2 r^{-\mu}$, the expected time variation in intensity from the matter can be described as $a/(\tau_0 - t)^{\alpha_0}$ where t is the time (set to be 0 when matter crosses the innermost radius r_{in} of the accretion disk), and $\alpha_0 = (\lambda+\mu)/(\lambda+1)$ and $\tau_0 = r_{in}^{\lambda+1}/(\lambda+1)C_1$ (Negoro, 1995b). This formula is exactly the fractal function used in describing the rise profiles.

This model is rather simple, but gives a relationship between the *observed* (*not assumed*) shot profiles and some physical parameters for the first time. Note that this function must (approximately) hold in any accretion model. Setting $\lambda = 1/2$ and $\mu = 2$, which are approximately correct in some accretion disk theories, gives $\alpha_0 = 5/3$, which is larger than the observed α. The observed shot profiles imply $\mu \sim 1$.

Thus, in this model, we just observe matter disappearing into a black hole as a shot. This was confirmed in a simulation based on the advection-dominated accretion flow (ADAF) model, in which some perturbation in the accretion disk gives rise to an intensity increase as it approaches the center (Mannmoto *et al.*, 1996). If so, where does the emission after the peak intensity come from ? The rapid spectral hardening at the peak intensity suggests that the radiative process suddenly changes. The above simulation also shows that, before disappearing into a black hole, the perturbation is reflected around the sonic point as an outgoing sound wave.

This successful model and simulation, however, do not explain all the properties of the shots. For instance, there are significant sub structures in the observed shots (see the ratios of the data to the model in Fig. 1.). Thus, the obtained shot profiles have more information on the vicinity of the central object. Studying the obtained shot properties will allow us to understand whether the shock occurs or not (Lu, 1998), whether emission comes from the inside of the innermost region of the accretion disk or not, and to know whether the black holes we imagine really exist or not.

The author thanks Lev Titarchuk for his useful comments on this work in this meeting, and Brad Rubin for a critical reading of the manuscript.

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