X-RAY STUDY OF MASS-ACCRETION FLOWS ONTO WEAKLY-MAGNETIZED NEUTRON STARS

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ABSTRACT

To investigate the physics of mass accretion onto weakly-magnetized neutron stars (NSs), which are often called low-mass X-ray binaries (LMXBs), energy spectra of 18 LMXBs observed by the RXTE satellite were analyzed. While the X-ray luminosity is sufficiently lower than the Eddington limit for a 1.4 $M_{\odot}$ NS, the energy spectra of the sample objects were represented successfully with a combination of two optically-thick components, one from a standard accretion disk and the other from the NS surface. As the accretion rate increases, the disk luminosity increased but that of the NS surface saturated or even decreased. When the mass accretion rate (hence the luminosity) becomes comparable to or even higher than the Eddington limit, the LMXB spectra were discovered to consist of three optically-thick components; the softest one from a retreated disk, the hardest one from the NS surface, and an additional intermediate component presumably from outflows caused by the increased radiation pressure.

Key words: stars: binaries: general — stars: individual(4U 1608-522, GX 5-1, GX 17+2) — stars: neutron — X-ray: stars .

1. INTRODUCTION

Physics of accretion flows (e.g., accretion disks), especially in black hole binaries, has been relatively well understood when the mass accretion rate $\dot{M}$ is moderate and hence the gravitational force dominates others. However, much less is known when the mass accrete is so high that the radiation pressure becomes comparable to the gravitation. In particular, observational confirmation of "outflows" of a portion of the accreting matter, which is expected under a high radiation pressure, has been very scarce.

To study the accretion flow under such a high accretion rate, LMXBs are one of the best targets. Since the mass of NSs, typically $\sim 1.4M_{\odot}$, is about an order of magnitude lower than those of black holes, the radiation pressure of an LMXB becomes significant even at relatively low accretion rates. Moreover, unlike black holes which could swallow the matter before it fully radiates, a NS has a solid surface with a radius ∼ 10 km; therefore, the matter cannot settle down to the bottom of the gravitational potential (i.e., the NS surface) without radiating away the acquired energy.

Employing the Eastern model (Mitsuda et al., 1984, 1989; Makishima et al., 1989), we analyzed a huge amount of publicly available data of 18 luminous LMXBs obtained by RXTE (Takahashi, 2005). When the X-ray luminosity of each LMXB is lower than the Eddington limit (2.1 $\times 10^{38}$ ergs^{-1}), all the spectra averaged per observation (typical exposures of ∼ ks) are well reproduced by the Eastern model, as exemplified in § 2. In § 3, we study two "Z-sources", GX 5-1 and GX 17+2, of which the luminosities are comparable to or even higher than the Eddington limit. Their properties are consistently explained by a modified Eastern model which incorporates significant matter outflows.

2. 4U 1608-522 IN UPPER BANANA BRANCH

Energy spectra of 4U 1608-522 in so called Upper Banana branch (UB) are well represented by the Eastern model with a combination of a soft multi-color disk (MCD) model and a hard blackbody (BB) emission, of which the temperatures are ∼ 1.5 and ∼ 2.5 keV, respectively. The former component represents emission from the optically-thick accretion disk, and the latter from the central NS. Figure 1 shows the 3–30 keV MCD luminosity $L_{\rm disk}$, the BB luminosity $L_{\rm BB}$ in the same band, and their sum $L_{\rm tot}$, as a function of $\dot{M}$ which is estimated from parameters of the MCD model (Mitsuda et al., 1984). It is clear that $L_{\rm disk}$ is well proportion to $\dot{M}$. Since $L_{\rm disk} \propto r_{\rm in}^2 T_{\rm in}^4$ and $\dot{M} \propto r_{\rm in}^3 T_{\rm in}^4$, where $r_{\rm in}$ and $T_{\rm in}$ are the innermost disk radius and temperature, respectively, this result implies that $r_{\rm in}$ is constant, namely the accretion disk exists stably. On the other hand, $L_{\rm BB}$ is seen to depend less steeply on $\dot{M}$. According to the virial theorem, a half of the released gravitational energy of the accreting matter should be radiated from the accretion disk as $L_{\rm disk}$, and the other half becomes the Keplerian energy of the matter which should be eventually radiated as $L_{\rm BB}$ if all the matter accretes onto the NS surface. In that case, $L_{\rm BB}$ should be proportion to $L_{\rm disk}$. Therefore, Figure 1 indicates that only a fraction of the mass flow through the disk reaches the NS surface, while the rest

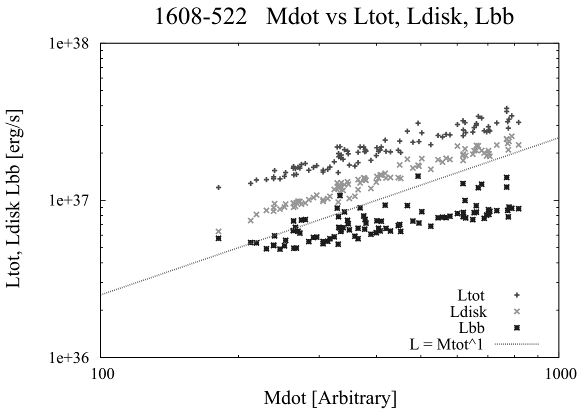

Figure 1. The dependences of $L_{\rm disk}$, $L_{\rm BB}$ and $L_{\rm tot}$ on $\dot{M}$, calculated over the 95 datasets of 4U 1608-522 in UB.

presumably forms outflows. Since the total luminosity $L_{\rm tot} \sim 4 \times 10^{37}$ erg s^{-1} is close to the Eddington limit, we suppose that the outflow is driven by radiation pressure. As the total luminosity increases, the ratio of $L_{\rm BB}$ to $L_{\rm disk}$ decreases from 0.6 to 0.4. Then, the fraction of the matter outflow is estimated to be $\sim$ 30% of $\dot{M}$.

3. GX 5-1 AND GX 17+2 IN FLARING BRANCH

To study the physical state under higher radiation pressure than that of 4U 1608-522, we analyzed “Flaring branch” (FB) data of two Z sources, GX 5-1 and GX 17+2, of which the luminosities (several times 10^{38} erg s^{-1}) reach the Eddington limit. They represent two subclasses of Z-sources; one class of the objects including GX 5-1 shows a decrease in the hard X-ray (10–40 keV) counts as they evolve deeper into FB, while the other class including GX 17+2 behaves in the opposite way. This difference between the two subclasses may be caused by inclination angles; namely the former is observed with higher inclinations, and the latter with lower ones (Kuulkers et al., 1994, 1996).

Figure 2 shows energy spectra of GX 5-1 and GX 17+2 in FB. Indeed, the spectrum of GX 5-1 is detected only up to $\sim$ 20 keV, while that of GX 17+2 reaches $\sim$ 30 keV. The GX 5-1 spectrum cannot be reproduced by a single MCD model (χ^2/d.o.f. $\sim$ 3), and needs the MCD and BB components (χ^2/d.o.f. $\sim$ 1.2). The temperatures and radii are obtained as $\sim$ 0.9 keV and $\sim$ 60 km for the MCD component, and $\sim$ 1.5 keV and $\sim$ 20 km for the BB. In contrast, we discovered that the GX 17+2 spectrum is well represented by the MCD and two BB (BB1 and BB2) models, of which the temperatures are $\sim$ 0.6 keV, $\sim$ 1.3 keV and $\sim$ 2.5 keV, respectively. The temperatures and radii of the softer two emission (MCD and BB1) are comparable with those of GX 5-1, whereas the hard BB2 component is not observed from GX 5-1.

In addition to the BB2 temperature $\sim$ 2.5 keV, of which the value is similar to those observed from 4U 1608-522, the radius of the BB2 emission region $\sim$ 4 km is also close to the NS radius. Therefore, the BB2 emission is considered to be emitted from the NS surface. The temperature and radius of the BB1 component are just in between those of the MCD (e.g. the accretion disk) and BB2 (NS surface) components. Since these Z sources should exhibit more enhanced outflows than 4U 1608-522 with the lower luminosity, we interpret that BB1 is emitted from the outflow which becomes optically thick.

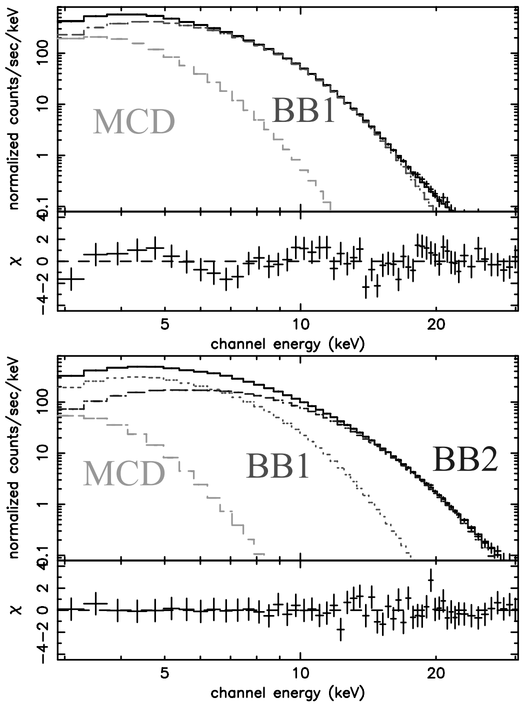

Figure 2. Energy spectra of GX 5-1 and GX 17+2 in FB, fitted with the MCD, BB1, and BB2 components.

These facts have led us to propose the following picture. (1) The innermost portion of the accretion disk becomes inflated due to its own radiation pressure, causing the optically-thick inner disk edge to retreat back and hence the temperature there to decrease. (2) Through the inflated inner disk, the matter partially accretes onto the NS surface, as a quasi-spherical flow, thus producing the BB2 component from the NS surface. (3) The rest of the matter keeps escaping as the outflow, and the increased optical depth of the outflow causes it to emit the BB1 component. (4) The BB1 emitter is not totally spherical, and obscures the BB2 region when viewed from a relatively edge-on inclination as in GX 5-1.

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