PROCEEDINGS OF SCIENCE

# Near-Infrared Observation of GRS 1915+105 in the Soft State

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We report detailed, long term near-infrared (NIR) light curves of GRS 1915+105 in 2007–2008, covering its long "soft state" for the first time. From our NIR monitoring and the X-ray data of the All Sky Monitor (ASM) onboard *Rossi X-ray Timing Explorer* (*RXTE*), we discovered that the NIR flux dropped by $>1$ mag during short X-ray flares with a time-scale of days. With the termination of the soft state, the $H-K_{\rm s}$ color reddened and the anti-correlation pattern was broken. The observed $H-K_{\rm s}$ color variation suggests that the dominant NIR source was an accretion disk during the soft state. The short X-ray flares during the soft state were associated with spectral hardening in X-rays and increasing radio emission indicating jet ejection. The temporal NIR fading during the X-ray flares, hence, implies a sudden decrease of the contribution of the accretion disk when the jet is ejected.

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## 1. Introduction

The microquasar GRS 1915+105 is one of the most intriguing sources in the X-ray, infrared and radio bands. The object was first observed in outburst in 1992 by the WATCH instrument on-board the GRANAT satellite ([2]). Radio observations led to the identification of a superluminal radio source with ejecting plasma clouds at $v \sim 0.92$c ([14]). From NIR spectroscopic observations, the companion star is classified as a K–M type giant. Its orbital period and the mass of the black hole were estimated to be $33.5 \pm 1.5$ days and $14 \pm 4$ $M_{\odot}$, respectively ([10], [11]).

GRS 1915+105 occasionally enters "long State A (or class $\phi$)" categorized in [1], sometimes referred as the "soft state". This state is characterized by a soft X-ray spectrum with a low flux level in the X-ray and radio regime. The origin of the soft X-ray emission is not clear, either an emission from the accretion disk with a high innermost temperature ($>$ 1 keV) and/or a Comptonized spectrum (e.g., [4]; [22]). weeks ([16]). Although the soft state is one of the fundamental, and hence, important phases for understanding the nature of GRS 1915+105, multi-wavelength studies have poorly been performed during this state due to its low incidence.

In August 2007, GRS 1915+105 newly entered the soft state after the last one in August 2005. Here, we report our results of long and continuous NIR photometric monitoring of GRS 1915+105 covering this state at Higashi-Hirosima Observatory, Japan. Based on our data, we reveal the NIR activity in the soft state in detail for the first time.

## 2. Observations and Data

### 2.1 NIR observations with the "KANATA" telescope

We performed NIR observations using TRISPEC (Triple Range Imager and SPECtrograph) attached to the "KANATA" 1.5-m telescope at Higashi-Hiroshima Observatory, Hiroshima, Japan. TRISPEC is a simultaneous imager and spectrograph with polarimetry covering both optical and near-infrared wavelengths ([23]). We used the imaging mode of TRISPEC with $H$ and $K_s$ filters with a dithering technique. Exposure times for each frame varied night by night between 14–28 and 7–14 s in $H$- and $K_s$-band images, respectively, depending on the sky condition. In a night, we typically took 10–20 images in total.

We measured $H$ and $K_s$ magnitudes of GRS 1915+105 using a comparison star in the same frame, which is located at R.A.=19:15'09".13, Dec.=+10D57'11".1 ($H = 10.820$, $K_s = 10.130$). We quated the $H$ and $K_s$ magnitudes of the comparison star from the 2MASS catalog [18]. We checked the constancy of the comparison star using neighbor stars and found that they exhibited no significant variations with amplitudes $\lesssim 0.1$ mag in both bands. In this paper, no correction was performed for the interstellar extinction.

### 2.2 Radio observations

All the radio data were obtained with North sector RATAN-600 radio telescope attached with a continuum radiometers at 4.8 and 11.2 GHz.

### 2.3 X-ray data

To estimate the daily flux level and hardness ratio in soft X-ray range, we used the public ASM/*RXTE* (1.5–12 keV) daily-averaged intensities, which were obtained from the MIT ASM web page [1]. In addition, we also use BAT/*Swift* (15–50 keV) light curve, which were obtained from the Swift/BAT team web page [2].

## 3. Results

Our observations are shown in figure 1. The panel (a) of figure 1 shows the $K_s$-band light curve obtained with TRISPEC/KANATA. The panel (b) depicts the temporal variations of $H - K_s$ colors. In the panel (c), (d) and (e), we show the X-ray data; the soft X-ray light curve (1.5–12 keV) and the hardness ratio ("HR2" defined as the flux ratio of C band (5-12 keV) / B band (3-5 keV) obtained by ASM/*RXTE*, and the hard X-ray light curve (15–50 keV) by BAT/*Swift*, respectively. We first describe the overall X-ray behavior of the object during our NIR monitoring, and then, report correlations of the NIR and X-ray fluxes.

### 3.1 X-Ray behavior during our NIR monitoring

Between MJD 54250 and 54320, GRS 1915+105 was in an active state with hard X-ray spectrum. A large flare occurred between MJD 54280 and 54320, accompanied with a large HR2 of $\sim 1.5$.

After the flare, GRS 1915+105 entered the "soft state" (state A) in $\sim$ MJD 54321, as indicated by the small hardness ratio and the low level flux of the soft and hard X-rays. According to [1], the soft state is defined by HR2$\lesssim$ 1.1. With this definition, the object stayed in the soft state almost all times from MJD 54321 to 54571. We note that the duration of this soft state is $\sim$ 250 d, much longer than those of the soft states previously observed in X-ray ($\sim$ 60 d in [21]).

During the soft state, the X-ray flux occasionally showed modulations and flares having a time-scale of days. At the peak of an X-ray flare on MJD 54368, the hardness ratio, HR2, was 1.3, which is higher than that in the soft state. Also in the other X-ray flares and modulations, we can see that HR2 was high in a range of 1.2 – 1.5. In the flare on MJD 54368, the flux increased by a factor of 3.4 and 17.7 in the ASM and BAT count rate, respectively. While the amplitudes in the flux density depend on the spectral index during the flare, the large HR2 and the large amplitude in the BAT count rate indicate that the X-ray flares had X-ray spectra harder than that in the ordinary soft state. Figure 2 shows the light curves in the X-ray, radio, and NIR ranges between MJD 54320 and 54450. On MJD 54368, at the peak of the X-ray flare, the radio flux significantly increased from $\sim$ 3 mJy to 223 mJy at 4.8 GHz and from $\sim$ 17 mJy to 202 mJy at 11.2 GHz. This radio flare indicates the emergence of the jet.

The soft state was terminated by the flare on $\sim$MJD 54571. After this flare, the hardness ratio abruptly increased on $\sim$MJD 54589, which indicates the occurrence of a state transition. The increase of the hard X-rays (the panel (e) of figure 1) also supports that the X-ray spectrum changed from the soft to the hard one. This state can be categorized as the "plateau state", which is

[1] http://xte.mit.edu/ASM_lc.html.

[2] http://swift.gsfc.nasa.gov/docs/swift/results/transients/index.html.

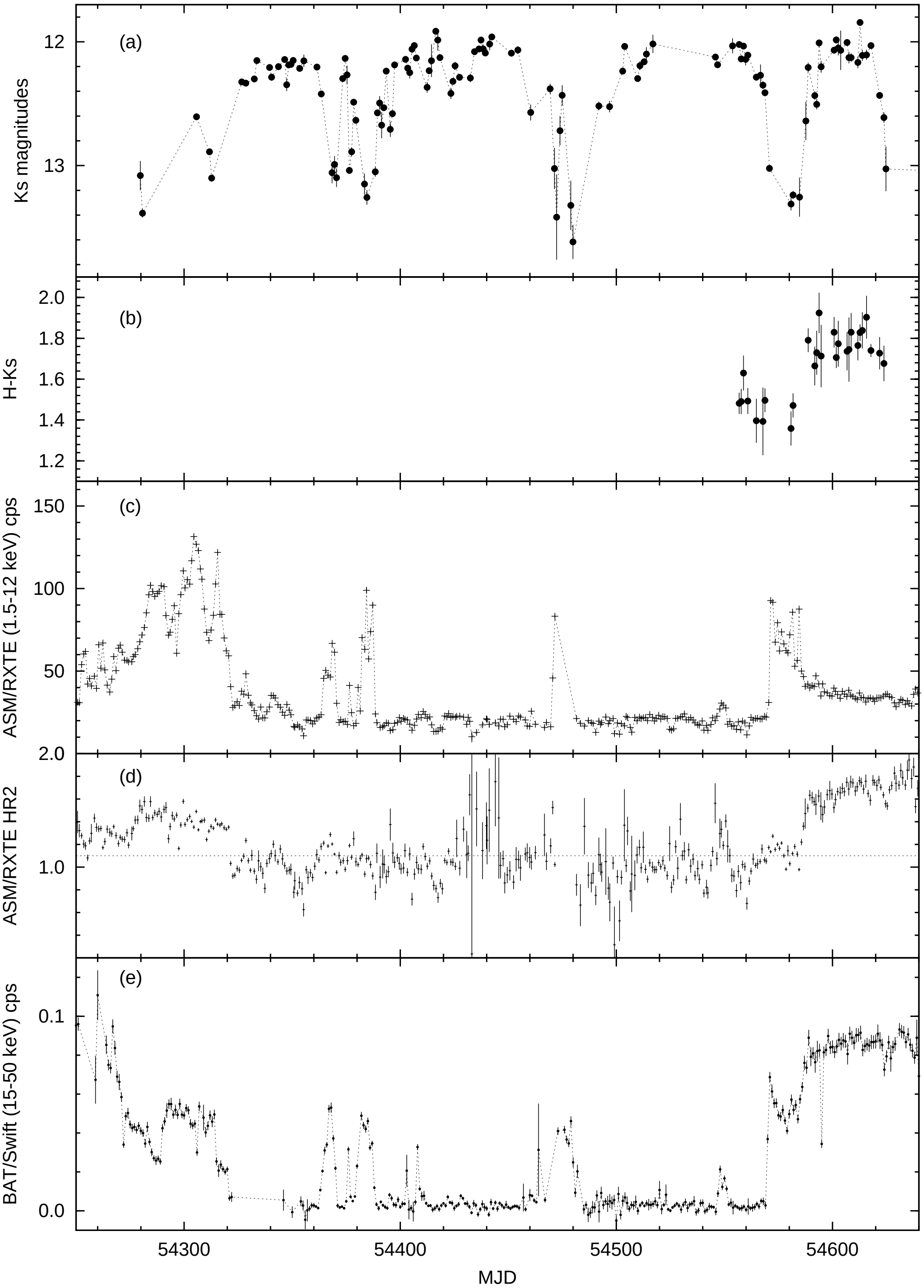


**Figure 1:** Light curves and the temporal variations of the NIR color and X-ray hardness ratio of GRS 1915+105. The abscissa denotes the time in MJD. (a) $K_s$-band light curve. (b) $H-K_s$ color variations. The reddening correction was not performed. (c) Soft X-ray light curve observed by ASM/*RXTE*. (d) Hardness ratio (HR2) by ASM/*RXTE*. According to [1], the object is considered to be in the soft state if HR2 is lower than the horizontal dashed line. (e) Hard X-ray light curve by BAT/*Swift*.

characterized by the prolonged hard X-ray emission associated with the steady synchrotron radio emission (e.g., [8]). Plateau states have a precursor flare (e.g., [13]). The plateau state in 2008 was also associated with a pre-plateau flare [19].

Except for the atypically long duration of the soft state, the overall X-ray behavior of GRS 1915+105 was a standard one in terms of the characteristics of the light curve ([1]). Owing to the long duration, we can investigate the correlation of the X-ray and the NIR fluxes during the soft state for the first time in detail.

### 3.2 Anti-correlation of the X-ray and NIR flux during the soft state

Before the soft state, the $K_s$-band flux was variable, possibly correlating with the X-ray flare on MJD 54280–54320, while our $K_s$-band observation was too sparse to be conclusive for the possible positive-correlation. The $K_s$-band flux, then, increased to $K_s \sim 12.2$ when the object entered the soft state and the X-ray flux reached a low level on $\sim$ MJD 54321.

In the soft state, we discovered a clear anti-correlation between the $K_s$-band and X-ray fluxes. In figure 1, the anti-correlation is evident during the prominent X-ray flares in MJD 54363–54370, 54382–54387, and 54470–54480, in which the $K_s$-band flux decreased when the X-ray flare occurred. Furthermore, we confirmed that the anti-correlation was present even for lower amplitude X-ray modulations, as indicated by the dashed lines in figure 2. A simple calculation of a correlation function suggests no significant time-lag between the X-ray and $K_s$-band flux over a day. There might be a possible time-lag shorter than a day, which is, however, difficult to be established with our available data.

This is the first time that such a clear anti-correlation was observed between the X-ray and NIR flux on a short time-scale of days during the soft state. We found that the similar anti-correlation behavior was probably seen in the light curve reported in [15], which observed the soft state in 2005 August. This anti-correlation behavior is, hence, probably a common feature for the soft state in GRS 1915+105.

On MJD 54570, the $K_s$-band flux decreased associated with the X-ray flare just before the state transition from the soft state to the plateau state. The object, then, re-brightened to $K_s = 12.1 \pm 0.1$ and stayed in that level during the plateau state. As can be seen from the panels (a) and (e) of figure 1, the anti-correlation feature between the NIR and the X-ray flux was apparently broken after this state transition; the X-ray flux in the plateau state was higher than that in the soft state, while the NIR flux in the plateau state kept a high level as in the soft state.

As shown in the panel (b) of figure 1, the $H-K_s$ color was relatively blue during the soft state ($H-K_s = 1.47 \pm 0.08$). The color abruptly changed to be redder on MJD 54584 when the X-ray state transition started, as shown in the hardness ratio variation (the panel (d) in figure 1). During the plateau state, the average of the color was $H-K_s = 1.77 \pm 0.07$, significantly redder than that in the soft state.

These results indicate that the dominant NIR emission source changed due to the state transition. In other words, the state transition occurred not only in the X-ray regime, but also in the NIR one. It is interesting to note that the maximum $K_s$-band flux level in the plateau state was quite similar to that in the soft state, both at $K_s \sim 12.1$, although the dominant emission source changed.

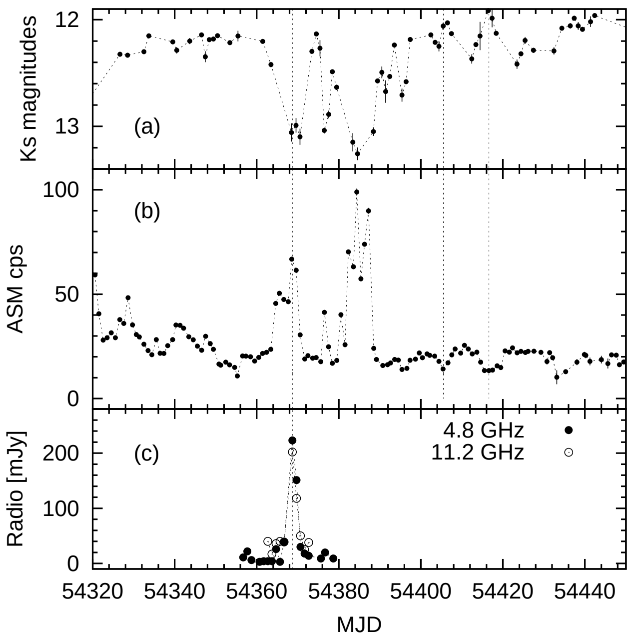


**Figure 2:** Multiwavelength light curves between MJD 54320 and 54450. (a) $K_s$-band light curve. (c) Soft X-ray light curve observed by ASM/*RXTE*. (b) Radio light curves in 4.8 GHz and 11.2 GHz. The vertical dashed lines are shown in order to readily see the anti-correlation of the NIR and X-ray fluxes.



## 4. Discussion

In ordinary X-ray binaries, the NIR sources can be companion stars, accretion disks, or jets (e.g; [12]; [3]). Here, we discuss which component was dominant and responsible for the intriguing anti-correlation of the NIR and X-ray variations in the soft state.

The most promising candidate is the accretion disk. First, the accretion disk can be variable with a short time-scale of days. Second, the $H - K_s$ color was bluer in the soft state than that in the plateau one. We can expect that the NIR emission originates from the outermost part of the accretion disk ($T \sim 10^4$ K), whose $H - K_s$ color is presumably bluer than those of the companion star (K–M giant) and the synchrotron jet.

The jet is less likely for the NIR source in the soft state because the radio emission was quite weak, except for the period of the X-ray flares. During the X-ray flare, figure 2 shows an anti-correlation of the NIR and radio flux, which has a negative implication for the jet scenario. We can reasonably reject the companion star origin because it is hard for a K–M-type giant star to be variable with the amplitude of $\sim 1$ mag within a few days. Moreover, there is no sign for orbital period variations in our light curve.

By contrast, after the transition to the plateau state, the dominant NIR source could be changed from the accretion disk to the jet, as suggested by previous authors ([20]; [9]; [5]). In fact, the radio emission during the plateau state is considered to originate from the steady, compact jet ([8]).

The temporal fading of the NIR flux during the X-ray flares, thus, implies that the contribution of the accretion disk decreases when the jet is ejected. The mechanism of this anti-correlated variation is, however, totally unknown. If the soft state of GRS 1915+105 is analogous to the "high/soft state" of ordinary black hole candidates, the standard accretion disk can be the dominant source in the NIR to X-ray band [17, 6]. In this case, the NIR flux should correlate with the X-ray one because both fluxes are a function of the mass accretion rate in the disk. This is opposite to our observations. We, thus, need alternative factors for understanding the anti-correlation feature, for example, the irradiation and/or reprocess by X-ray emission at the outermost part of the accretion disk, or the occultation of the NIR source by the jet or disk.

## 5. Summary

We reported detailed NIR behavior of GRS 1915+105 during the soft state for the first time. The object entered the soft state (long State A) in August 2007. Our results revealed a clear anti-correlation between the NIR and X-ray fluxes in the soft state. This feature was also confirmed for small amplitude modulations. After the termination of the soft state, the object entered the plateau state, where the anti-correlation pattern was broken. Based on the $H-K_\mathrm{s}$ color variation, we propose that the dominant NIR source was an accretion disk in the soft state. Since the X-ray flares during the soft state were associated with the jet ejection, our observation suggests that the contribution of the accretion disk decreases when the jet is ejected.

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