Anti-Correlation of the Near-Infrared and X-Ray Variations of the Microquasar GRS 1915+105 in Soft State

Akira Arai¹, Makoto Uemura², Mahito Sasada³, Sergei A. Trushkin⁴, Yoshihiro Ueda⁴, Hiromitsu Takahashi⁵, Koji S. Kawabata³, Masayuki Yamanaka², Osamu Nagae⁵, Yuki Ikejiri¹, Kiyoshi Sakimoto¹, Risako Matsui¹, Takashi Ohsugi¹,², Takuya Yamashita², Mizuki Isogai³, Yasushi Fukazawa¹, Tsunefumi Mizuno¹, Hideaki Katagiri¹, Kiichi Okita⁶, Michitoshi Yoshida⁶, Kenshi Yanagisawa⁶, Shuji Sato⁷, Masaru Kino⁷ and Kozo Sadakane⁸

¹ Department of Physical Science, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526
² Hiroshima Astrophysical Science Center, Hiroshima University, Kagamiyama 1-3-1, Higashi-Hiroshima 739-8526
³ Special Astrophysical Observatory of Russian Academy of Science (SAO-RAS), Nizhnij Arkhyz, Karachai-Cherkessia, 369167, Russia
⁴ Department of Astronomy, Kyoto University, Sakyo-ku, Kyoto 606-8502
⁵ Ishigakijima Astronomical Observatory, National Astronomical Observatory of Japan, Arakawa 1024-1, Ishigaki, Okinawa 907-0024
⁶ Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Kamogata, Okayama 719-0232
⁷ Department of Physics, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8602
⁸ Astronomical Institute, Osaka Kyokai University, Asahigaoka, Kashiwara, Osaka 582-8582

(Received ; accepted )

Abstract

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 – Ks color reddened and the anti-correlation pattern was broken. The observed H – Ks 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.

Key words: stars: individual (GRS 1915+105) — stars: binaries — infrared:stars — accretion disks

1. Introduction

The black hole X-ray binary GRS 1915+105 is well-known and one of the most intriguing and variable galactic 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 (Castro-Tirado et al. 1992; Castro-Tirado et al. 1994). Radio observations led to the identification of a superluminal radio source with ejecting plasma clouds at v ∼ 0.92c (Mirabel and Rodríguez 1994). These radio jets and their superluminal motion are reminiscent of quasars, and hence this source is called a “microquasar”. Using the motion of the relativistic jets, Fender et al. (1999) estimated an upper limit of the distance to be 11.2 ±0.8 kpc. 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 ± 1.5 days and 14 ± 4 M⊙, respectively (Greiner et al. 2001a,b).

GRS 1915+105 occasionally enters “long State A (or class φ)” categorized in Belloni et al. (2000), 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., Done et al. 2004; Ueda et al. 2009). This state has been observed once a few years and typically continued for several weeks (Reig et al. 2003). Since the source spends the most time in the low/hard regime (State C in Belloni et al. 2000), the occurrence rate of the soft state is low. 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 at Higashi-Hiroshima Observatory covering this state. Based on our data, we reveal the NIR activity in the soft state in detail for the first time. In
§ 2, we describe our NIR observations and archived X-ray data. In § 3, we report new observational aspects obtained from our monitoring; the anti-correlation of NIR and X-ray bands in the soft state. In § 4, we discuss the origin of the NIR emission. Finally, we summarize our findings in § 5.

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. TRISPEC is a simultaneous imager and spectrograph with polarimetry covering both optical and near-infrared wavelengths (Watanabe et al. 2005). We used the imaging mode of TRISPEC with $H$ and $K_s$ filters. Exposure times for each frame varied by night between 14–28 and 7–14 s in $H$ - and $K_s$-band images, respectively, depending on the sky condition. We adopted a dithering technique, consisting of five sequential exposures at different neighboring positions around the objects. In a night, we typically took a few sequences, that is, 10–20 images in total.

After making sky-subtracted and flat-fielded images, 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.$=19^h 15^m 09^s 13$, Dec.$=+10^\circ 57^\prime 11^\prime\prime 1$ ($H=10.820$, $K_s=10.130$). We quote the $H$ and $K_s$ magnitudes of the comparison star from the 2MASS catalog (Skrutskie et al. 2006). We checked the constancy of the comparison star using neighbor stars and found that they exhibited no significant variations with amplitudes larger than 0.1 mag in $H$ and $K_s$ band. 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 BAT/Swift 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 $f_{5–12 \, \text{keV}} / f_{3–5 \, \text{keV}}$) 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 $\sim 1.5$.

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 Belloni et al. (2000), the soft state is defined by HR2 $\leq 1.1$. 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 ($\sim 60$ d in Ueda et al. 2006).

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 233 mJy at 4.8 GHz and from $\sim 17$ mJy to 202 mJy at 11.2 GHz.

In previous radio observations of GRS 1915+105, three types of radio flares are known (Eikenberry et al. 2000). The class A flare is characterized by long durations (several days) and large amplitudes. It is believed to be associated with major jet ejections (Mirabel and Rodriguez 1994; Fender et al. 1999). The class B and C flares are consecutive short ($\sim 500–1800$ s) flares (e.g. Fender et al. 1997; Mirabel et. al. 1998; Feroci et al. 1999; Eikenberry et al. 2000). Thus, the flare on MJD 54368 was presumably a class A flare, associated with the jet ejection, based on the duration and amplitudes of the flare.

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 characterized by the prolonged hard X-ray emission associated with the steady synchrotron radio emission (e.g., Foster et al. 1996). Plateau states have a precursor flare (e.g.,

1. (http://xte.mit.edu/ASM_lc.html).
2. (http://swift.gsfc.nasa.gov/docs/swift/results/transients/index.html).
Klein-Wolt et al. 2002). The plateau state in 2008 was also associated with a pre-plateau flare (Trushkin et al. 2008).

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 (Belloni et al. 2000). 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 Neil et al. (2007), 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, rebrightened 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

![Fig. 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 Belloni et al. (2000), 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.](image-url)
quite similar to that in the soft state, both at the maximum but also in the NIR one. It is interesting to note that the state transition occurred not only in the X-ray regime, 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 $\sim 12$ magnitudes, whereas in the soft state it was $\sim 1$ magnitudes 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 (Ueda et al. 2002; Fuchs et al. 2003; Eikenberry et al. 2008). In fact, the radio emission during the plateau state is considered to originate from the steady, compact jet (Foster et al. 1996).

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 (Shakura & Sunyaev 1976; Esin et al. 1997). 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, as reported in (Ueda et al. 2002). 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. If the irradiation or reprocess effect plays a key role, a short time-lag may be observed between the NIR and X-ray variations because of long heating and cooling time-scales in the outer part of the disk. Dense multi-wavelength observations are required to reveal the nature of the observed anti-correlation.

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 $H-K_s$ 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.

This work was partly supported by a Grand-in-Aid from the Ministry of Education, Culture, Sports, Science, and Technology of Japan (19740104, 17340054). Research has made use of BAT/\textit{Swift} transient monitor results provided by the BAT/\textit{Swift} team.

References

Belloni, T., Klein-Wolt, M., Méndez, M., van der Klis, M., & van Paradijs, J. 2000, A&A, 355, 271
Castro-Tirado, A. J., Brandt, S., & Lund, N. 1992, IAU Circ., 5590, 2
Castro-Tirado, A. J. and Brandt, S. and Lund, N. and Lapshov, I. and Sunyaev, R. A. and Shlyapnikov, A. A. and Guzy, S. and Pavlenko, E. P. 1994, ApJS, 92, 469
Chaty, S., Haswell, C. A., Malzac, J., Hyne, R. I., Sirrader, C. R., & Cui, W. 2003, MNRAS, 346, 689
Done, C. and Wardziński, G. and Gierliński, M. 2004, MNRAS, 349, 393
Eikenberry, S. S. and Matthews, K. and Morgan, E. H. and Remillard, R. A. and Nelson, R. W. 1998, ApJL, 494, L61
Eikenberry, S. S. and Matthews, K. and Muno, M. and Bianco, P. R. and Morgan, E. H. and Remillard, R. A. 2000, ApJL, 532, L33
Eikenberry, S. S., Patel, S. G., Rothstein, R., Pooley, G. G., & Morgan, E. H. 2008, ApJ, 678, 369
Esin, A. A., McClintock, J. E., & Narayan, R. 1997, ApJ, 489, 865
Fender, R. P. and Pooley, G. G. and Brocksopp, C. and Newell, S. J. 1997, MNRAS, 290, L65
Fender, R. P., Garrington, S. T., McKay, D. J., Muxlow, T. W. B., Pooley, G. G., Spencer, R. E., Stirling, A. M., & Waltman, E. B. 1999, MNRAS, 304, 865
Feroci, M. and Matt, G. and Pooley, G. and Costa, E. and Tavani, M. and Belloni, T. 1999, 351, 985
Foster, R. S., Waltman, E. B., Tavani, M., Harmon, B. A., Zhang, S. N., Paciesas, W. S., & Ghigo, F. D. 1996, ApJL, 467, L81
Fuchs, Y., Mirabel, I. F., & Claret, A. 2003, A&A, 404, 1011
Greiner, J., Cuby, J. G., McCAughrean, M. J., Castro-Tirado, A. J., & Mennickent, R. E. 2001a, A&A, 373, L37
Greiner, J., Cuby, J. G., & McCAughrean, M. J. 2001b, Nature, 414, 522
Haswell, C. A., King, A. R., Murray, J. R., & Charles, P. A. 2001, MNRAS, 321, 475
Klein-Wolt, M., Fender, R. P., Pooley, G. G., Belloni, T., Migliari, S., Morgan, E. H., & van der Klis, M. 2002, MNRAS, 331, 745
Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46
Mirabel, I. F. and Dhawan, V. and Chaty, S. and Rodriguez, L. F. and Marti, J. and Robinson, C. R. and Swank, J. and Geballe, T. 1998, A&A, 330, L9
Neil, E. T., Bailyn, C. D., & Cobb, B. E. 2007, ApJ, 657, 409
Reig, P., Belloni, T., & van der Klis, M. 2003, A&A, 412, 229
Shakura, N. I. and Sunyaev, R. A. 1976, MNRAS, 175, 613
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Trushkin, S., Nizhebskij, A. N., & Bursov, N. N. 2008, The Astronomer’s Telegram, 1509, 1
Ueda, Y., et al. 2002, ApJ, 571, 918
Ueda, Y., et al. 2006, Proceedings of the VI Microquasar Workshop: Microquasars and Beyond. September 18–22, 2006, Como, Italy., p.23.1
Ueda, Y., Yamaoka, K., & Remillard, R. 2009, ApJ, in press
Watanabe, M., et al. 2005, PASP, 117, 870