LONG-TERM MULTI-WAVELENGTH STUDIES OF GRS 1915+105. I. A HIGH-ENERGY AND MID-INFRARED FOCUS WITH RXTE/INTEGRAL AND SPITZER

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ABSTRACT

To date, mid-infrared properties of Galactic black hole binaries have barely been investigated in the framework of multi-wavelength campaigns. Yet, studies in this spectral domain are crucial to get complementary information on the presence of dust and/or on the physical processes such as dust heating and thermal bremsstrahlung. Here, we report a long-term multi-wavelength study of the microquasar GRS 1915+105. On the one hand, we aimed at understanding the origins of the mid-infrared emission, and on the other hand, at searching for correlation with the high-energy and/or radio activities. We observed the source at several epochs between 2004 and 2006 with the photometer IRAC and spectrometer IRS, both mounted on the Spitzer Space Telescope. When available, we completed our set of data with quasi-simultaneous RXTE/INTEGRAL high-energy and/or Ryle radio observations from public archives. We then studied the mid-infrared environment and activities of GRS 1915+105 through spectral analysis and broadband fitting of its radio to X-ray spectral energy distributions. We detected polycyclic aromatic hydrocarbon molecules in all but one IRS spectra of GRS 1915+105 which unambiguously proves the presence of a dust component, likely photoionized by the high-energy emission. We also argue that this dust is distributed in a disk-like structure heated by the companion star, as observed in some Herbig Ae/Be and isolated cool giant stars. Moreover, we show that some of the soft X-ray emission emanating from the inner regions of the accretion disk is reprocessed and thermalized in the outer part. This leads to a mid-infrared excess that is very likely correlated to the soft X-ray emission. We exclude thermal bremsstrahlung as contributing significantly in this spectral domain.

Key words: accretion, accretion disks – binaries: close – dust, extinction – infrared: stars – stars: individual (GRS 1915+105) – X-rays: binaries

1. INTRODUCTION

In a multi-wavelength study of microquasars, the infrared presents a particular interest as the accretion disk, the jets, or the companion star may all be detected. Nevertheless, most of the previous studies focused on the accretion–ejection phenomena as seen are X-ray/near-infrared/radio correlations and did not take the mid-infrared (MIR) emission into account (see, e.g., Mirabel et al. 1998; Ueda et al. 2002; Corbel & Fender 2002; Corbel et al. 2003; Chaty et al. 2003; Homan et al. 2005; Chaty & Bessolaz 2006; Russell et al. 2006). Yet, getting both MIR photometric and spectroscopic information is crucial to investigate the presence of dust, the disk illumination, thermal bremsstrahlung from the accretion disk’s wind, or the contribution of relativistic ejecta.

1.1. GRS 1915+105

Discovered by the WATCH all-sky X-ray monitor on board the GRANAT satellite, on 1992 August 15 (Castro-Tirado et al. 1992, 1994), GRS 1915+105 is the first microquasar in which apparent superluminal radio ejecta were detected (Mirabel & Rodriguez 1994). The nature of its companion star was the subject of debate until Greiner et al. (2001b) unambiguously showed that it was a K/M red giant by detecting CO absorption features in its near-infrared (NIR) spectrum. Moreover, the orbital period of the system and the mass of the compact object were found to be 33.5 ± 1.5 days (recently refined to 30.8 ± 0.2 day; Neil et al. 2007) and 14 ± 4 M⊙, respectively (Greiner et al. 2001a). The inclination is 66° ± 2°, and estimates of the distance fall in the range 6–12 kpc (Chaty et al. 1996; Fender et al. 1999; Chapuis & Corbel 2004).

GRS 1915+105 is strongly variable on timescales from seconds to days. Using extensive RXTE timing observations, Belloni et al. (2000) showed that its X-ray behavior could be divided in 12 distinct luminosity classes (up to 14 to date, Klein-Wolt et al. 2002; Hannikainen et al. 2003), and that the source was carrying out transitions between three canonical spectral states, labeled A, B (strong disk domination), and C (corona-dominated, no disk). Previous multi-wavelength studies showed the existence of a strong connection between the accretion disk instabilities and plasma outflows. In particular, discrete ejecta, emitting through optically thin synchrotron, are believed to be triggered during the transition between the C and A states, expanding adiabatically in the environment and detectable gradually from the NIR to the radio domains (see, e.g., Mirabel et al. 1996, 1998; Fender et al. 1997; Eikenberry et al. 1998, 2000; Rodriguez et al. 2008a, 2008b). Moreover, the other known class of radio ejecta—the compact jets emitting simultaneously from the radio to the NIR through optically thick synchrotron—are only detected in the χ luminosity class, which is only seen in the C state. The presence of such a jet is characterized by a flat spectrum with a roughly constant flux density between 50 and 100 mJy. Long periods of the χ luminosity class during which compact jets are present are called plateau and often precede or follow a giant ejection (see,
2. OBSERVATIONS AND DATA ANALYSIS

We performed, between 2004 October 2 and 2006 June 5, 16 photometric and spectroscopic observations of GRS 1915+105 with the IRAC photometer and the Infrared Spectrograph (IRS; PI: Y. Fuchs), both mounted on the Spitzer Space Telescope. Moreover, we completed our set of MIR observations with quasi-simultaneous high-energy observations, including INTEGRAL data already presented in great detail in Rodríguez et al. (2008a, 2008b; revolution 373) and several monitoring observations with RXTE (PI: Morgan; the data are immediately public). We finally also made use of observations of GRS 1915+105 obtained at 15 GHz with the Ryle Radio Telescope (PI: G. G. Pooley). Table 1 lists all the data we used in this study. In the following, for each quasi-simultaneous X-ray/MIR/radio observation, we will refer to the integer part of the MIR observation date.

2.1. Spitzer’s MIR Observations

GRS 1915+105 was observed with IRAC at 3.59, 4.50, 5.80, and 8.00 μm. Each image was the combination of 24 sub-exposures of 10 s each, giving a total integration time of 240 s in each filter. We performed photometry on the Basic Calibration Data (BCD) using the software MOsaicker and Point source EXtractor (MOPEX) v18.2.2. BCD data are raw data on which the Spitzer pipeline performs dark subtraction, multiplexer bleed correction, detector linearization, flat fielding, cosmic ray detection, and flux calibration. We used MOPEX for pointing refinement, mosaicking, co-addition, and flux measurements through point-spread function fitting in a 3 pixel radius aperture. They were then scaled to a 10 pixel aperture using the aperture-correction factors as given in the IRAC manual.

The source was always detected in all filters, and the absorbed fluxes are listed in Table 2. The uncertainties include the 3% systematic errors due to flux calibration instabilities (Reach et al. 2005).

Spectroscopy was performed with IRS using the SL2 (5.20–7.70 μm), SL1 (7.40–14.50 μm), LL2 (14.00–21.30 μm),}

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### Table 1

Summary of All the Spitzer’s Data of GRS 1915+105 We Made Use of in This Study

| IRAC | IRS | RXTE | INTEGRAL | Ryle | Ryle fluxes (mJy) | Class |
|------|-----|------|---------|------|------------------|-------|
| ... | 53280.275 | 53280.241–53280.348 | ... | 53280.636–53280.746 | <1 | ρ |
| 53284.176 | 53284.177–53284.236 | ... | ... | 53283.673–53283.706 | <1 | ρ |
| ... | 53293.226 | ... | ... | 53298.587–53298.663 | <1 | ... |
| 53308.741 | ... | ... | ... | 53308.811–5308.841 | <1 | ... |
| ... | 53484.099 | ... | ... | 53484.027–53484.169 | 76–91 | ... |
| 53496.287 | ... | ... | ... | 53496.209–53496.230 | 37–43 | ... |
| 53500.571 | 53500.362–53500.430 | ... | ... | 53500.202–53500.358 | 22–32 | δ |
| ... | 53511.697 | ... | ... | ... | ... | ... |
| 53636.571 | ... | ... | ... | ... | ... | ... |
| ... | 53660.072 | 53659.982–53660.079 | ... | 53659.577–53659.906 | 27–47 | φ |
| ... | 53661.182 | 53661.706–53661.856 | ... | 53660.602–53660.881 | 18–55 | φ |
| 53676.070 | 53676.247–53677.488 | ... | ... | 53675.583–63675.641 | 64–75 | χ, μ, β |
| ... | 53851.419 | 53851.307–53851.319 | ... | 53851.102–53851.320 | <3 | χ |
| 53857.587 | ... | ... | ... | ... | ... | ... |
| 53874.818 | ... | ... | ... | ... | ... | ... |
| 53890.827 | 53892.047–53892.063 | ... | ... | 53888.239–53888.261 | <1 | ρ |

**Notes.** For each instrument, we give the day of observation (in MJD) and, when available, the day of quasi-simultaneous coverage with RXTE, INTEGRAL and/or the Ryle telescope, as well as the Ryle flux level (15 GHz) in mJy. Moreover, when high-energy observations were available, we give the spectral class of the source as defined in Belloni et al. (2000).
Table 2

| MID      | 3.59 μm | 4.50 μm | 5.80 μm | 8.00 μm |
|----------|---------|---------|---------|---------|
| 53284    | 5.70 ± 0.17 | 5.32 ± 0.16 | 4.80 ± 0.15 | 3.12 ± 0.10 |
| 53308    | 5.26 ± 0.16 | 4.85 ± 0.15 | 4.32 ± 0.13 | 2.95 ± 0.10 |
| 53496    | 6.69 ± 0.26 | 6.12 ± 0.24 | 7.61 ± 0.23 | 5.03 ± 0.16 |
| 53500    | 10.28 ± 0.31 | 10.09 ± 0.30 | 8.80 ± 0.27 | 6.14 ± 0.19 |
| 53636    | 6.20 ± 0.19 | 5.88 ± 0.18 | 5.33 ± 0.16 | 3.77 ± 0.12 |
| 53676    | 10.70 ± 0.32 | 10.31 ± 0.31 | 9.15 ± 0.28 | 6.41 ± 0.20 |
| 53857    | 4.82 ± 0.15 | 4.75 ± 0.14 | 4.23 ± 0.13 | 2.87 ± 0.09 |
| 53890    | 5.16 ± 0.16 | 4.92 ± 0.15 | 4.36 ± 0.13 | 3.05 ± 0.10 |

Note. Uncertainties are given at 1σ and include 3% systematic errors.

and LL1 (19.50–38.00 μm) modules with the IRS peak-up option for a better pointing accuracy. Total exposure times were set to 120 s, divided in two sub-exposures in SL1 and SL2, and 300 s divided in 10 sub-exposures in LL1 and LL2. BCD data were reduced following the standard procedure given in the IRS Data Handbook. The basic steps were bad pixel correction, sky subtraction, as well as extraction and calibration (wavelength and flux) of the spectra—with the Spitzer IRS Custom Extraction software Spicex v2.1.2—for each nod. Spectra were then nod-averaged to improve the signal-to-noise ratio (S/N). In SL1 and SL2, GRS 1915+105 was always detected with S/N good enough to allow spectroscopic features identification (S/N > 10), as shown in Figure 1. Unfortunately, in LL1 and LL2, we never managed to detect the source.

2.2. RXTE Observations

The RXTE data were reduced with the LHEASOFT v. 6.7. All data products were extracted from user’s good times intervals (GTIs). GTIs corresponded to times when the satellite elevation was greater than 10° above the Earth limb, the offset pointing less than 0:02, and proportional counter unit 2 was active. In order to identify the classes, we extracted 1 s resolution light curves in the 2–60 keV range and in the three energy bands defined in Belloni et al. (2000), from the Proportional Counter Array (PCA). These bands are 2.0–5.7 keV (channels 0–13, PCA epoch 5), 5.7–14.8 keV (channels 14–35), and >14.8 keV (channels 36–255). The colors were defined as HR1 = 5.7–14.8/2.0–5.7 keV and HR2 = 14.8–60.0/2.0–5.7 keV. The shift of gain between the different epochs of PCA leads to different absolute values of the count rates, hardness ratios (HRs), and position in the color–color diagrams, but the general shape of a given class is easily comparable to those of epoch 3 (Belloni et al. 2000), and therefore allowed us to easily identify the variability class in each observation (see Rodriguez et al. 2008a). Light curves of 16 s resolution were extracted from standard two data between 2.0 and 18.0 keV. All these light curves were corrected for background, using the latest PCA background models available for bright sources. Spectra, including those showing clear spectral variations, were then extracted and averaged over the entire observations for a better spectral fitting.

2.3. INTEGRAL Observations

Our study makes use of the INTEGRAL Soft Gamma-Ray Imager (ISGRI; Lebrun et al. 2003)—the low energy detector of the Imager On-Board INTEGRAL (IBIS)—to cover the 18.0 to ~300.0 keV energy range, and the X-ray monitors JEM—X (Lund et al. 2003) to cover the 3.0–30.0 keV one. The data reduction process can be found in Rodriguez et al. (2008a, 2008b).

2.4. MIR Data Dereddening

The MIR data were dereddened from an optical absorption 

\[ A_V = 19.6 ± 1.7 \] 

(Chapuis & Corbel 2004) using the extinction laws given in Chiar & Tielens (2006). In their paper, the authors derived the \( A_I / A_K \) ratio rather than the usual \( A_I / A_V \) ones. To express the absorption ratio in a standard way, we assigned to \( A_K \) the value derived using the extinction law given in Fitzpatrick (1999) for the diffuse interstellar medium (ISM; \( R_V = 3.1 \)), which is \( A_K = 0.111 × A_V \). Although it has recently been demonstrated that the long-believed universal NIR extinction curve showed sharp variations depending on the line of sight (Fitzpatrick & Massa 2009 and references therein), these variations are rather observed outside of the Galactic plane (Galactic center excluded), and our choice to fix \( R_V \) to the value of the diffuse ISM has no strong incidences in the dereddening of the GRS 1915+105 data.

Moreover, if the authors give a universal expression up to 8.00 μm, they then propose two laws that take silicate absorption at 9.70 and 18.00 μm into account. Both differ in the sense that one is valid for the diffuse ISM and the other one for the Galactic center. Our absorbed MIR spectra exhibit a strong silicate absorption feature at 9.70 μm, and we tried to deredden each of them using both laws. The best results were systematically obtained with the modeling of interstellar extinction due to the diffuse ISM, the silicate feature in the Galactic center being too strong.

3. RESULTS

3.1. Light Curves

The fluxes listed in Table 2 show that GRS 1915+105 is strongly variable in all the IRAC filters, which confirms the variation detected by Fuchs et al. (2003a). The first step of our study was to compare the evolution of the source’s MIR emission with its X-ray and radio ones. Figure 2 displays the 3.59 μm (IRAC), 1.2–12 keV (All-Sky Monitor—ASM), and 15 GHz (Ryle) light curves of GRS 1915+105 covering the time interval from MJD 53200 to MJD 53900. Although we cannot claim for a correlation in the existing data, it is noticeable that the source is at its minimum level of MIR emission (or rather the minimum level of our measurements) when the microquasar has a steady and relatively low X-ray activity (around MJD 53280, 53308, and Table 1). Nevertheless, it is important to point out that during all our spectroscopic and photometric observations, GRS 1915+105 has never been found in the plateau state; an MIR emission from the compact jets can consequently be excluded from now on. Each time the Ryle flux is high, the source is
Figure 1. IRS spectra of GRS 1915+105 from 5.20 to 14.50 μm. All detected features are marked. For the MJD 53511 spectrum, the arrows mark the position of the undetected 7.7 and 11.25 μm PAH features.

rather in the decaying phase of a giant discrete ejection, whose emission is optically thin. This MIR/radio bimodal relation is therefore very likely related to the disk activity.

3.2. RXTE/INTEGRAL SEDs

The quasi-simultaneous high-energy spectra were fitted in ISIS v.1.5.0 between 3.0 (6.0) and 20.0 keV for PCA (JEM−X) as well as 20.0 and 200.0 keV for ISGRI and HEXTE. In most cases, they were further rebinned so as to obtain good quality spectra. We added 3% systematic errors to the uncertainties in the JEM−X spectra, 2% to the ISGRI ones, and 1% to the PCA ones before the fitting process. In all fits, a normalization constant was added to account for uncertainties in the cross calibration of the instruments.

The model we used during the fitting processes consisted in the combination of a multicolor black body (diskbb; Mitsuda et al. 1984), accounting for the accretion disk emission, a comptonization component (comptt; Titarchuk 1994) for the corona and a Gaussian for the iron feature at 6.4 keV when present, all modified by photo-electric absorption (phabs). The column density was fixed at $3.5 \times 10^{22}$ atoms cm$^{-2}$, as measured by Chapuis & Corbel (2004) from radio observations. If this value is consistent with some measurements derived from X-ray
observations (see, e.g., Ebisawa 1998; McClintock et al. 2006), several authors derived higher column densities clustered in the range 5–8 \times 10^{22} \text{ atoms cm}^{-2} (see, e.g., Klein-Wolt et al. 2002; Lee et al. 2002). Nevertheless, our attempts with higher values always gave equally good fits and did not change significantly the parameters of the disk and the comptonization components. Our goal being to fit broadband SEDs including both X-ray and MIR data, we decided to use the same column density value in both spectral domains.

A discussion on the validity of the use of comptt to model the hard X-ray emission can be found in Rodriguez et al. (2008b). Following the authors, the optical depth was fixed to 0.01, the lowest allowed value, when GRS 1915+105 was in the states A or B, during which the hard X-ray emission is better fitted by a power law. We made this choice of comptt because the use of a power law strongly overestimates the contribution of the corona at low energy and consequently underestimates the disk’s one, which has consequences in the optical and infrared domains. Moreover, a power law diverges once the data are dereddened, which forbids a spectral fitting from the X-rays to the MIR. comptt on the contrary peaks at 3kT_{\text{disk}} and is negligible in the optical and the infrared.

Finally, the Gaussian width was fixed at 0.8 keV and the iron line feature’s energy was allowed to vary between 5.0 and 7.0 keV. Table 3 gives the best-fit parameters found for the spectra obtained on MJD 53280, MJD 53284, MJD 53500, MJD 53676, MJD 53851, and MJD 53890; kT_{\text{disk}} and Norm are the accretion disk’s temperature and norm, and kT_e and \tau are the hard component’s electrons temperature and opacity. The spectra obtained on MJD 63660 and MJD 53661 did not need any disk component but an extra power law. Their best-fit parameters are listed in Table 4.

| Parameters          | MJD 53280 | MJD 53284 | MJD 53500 | MJD 53676 | MJD 53851 | MJD 53890 |
|---------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| kT_{\text{disk}} (keV) | 1.27^{+0.02}_{-0.02} | 1.29^{+0.02}_{-0.02} | 1.84^{+0.02}_{-0.02} | 2.05^{+0.04}_{-0.04} | 0.81^{+0.05}_{-0.05} | 1.28^{+0.07}_{-0.09} |
| Norm                | 594.0^{+40.7}_{-39.9} | 765.9^{+51.8}_{-46.2} | 267.5^{+12.0}_{-11.3} | 90.99^{+9.82}_{-8.18} | 1193.0^{+386.6}_{-294.6} | 3968.7^{+785.5}_{-553.3} |
| kT_e (keV)          | 158.8^{+3.7}_{-3.6} | 155.2^{+3.0}_{-2.9} | 118.1^{+8.4}_{-7.9} | 158.2^{+7.8}_{-7.3} | 27.3^{+13.7}_{-6.6} | 131.7^{+10.9}_{-9.9} |
| \tau                | 0.01 (frozen) | 0.01 (frozen) | 0.01 (frozen) | 0.04 (frozen) | 0.95^{+0.37}_{-0.39} | 0.01 (frozen) |
| F_{\text{total}}^a (\times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}) | 3.08 | 3.49 | 4.64 | 4.59 | 1.71 | 2.13 |
| F_{\text{disk}}^a (\times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}) | 1.22 | 1.19 | 3.75 | 3.74 | 0.20 | 0.85 |
| \chi^2 (d.o.f)       | 0.93 (53) | 1.09 (53) | 1.29 (53) | 1.65 (49) | 1.31 (53) | 1.25 (53) |

Notes. The best-fit model is phabs(diskbb+gaussian+comptt), and the error bars are given at the 90% confidence level. These spectra were built with RXTE/PCA+HEXTE data, except on MJD 53676 for which we used INTEGRAL/JEM–X+ISGRI data.

\textsuperscript{a} F_{\text{total}} and F_{\text{disk}} are the total and disk unabsorbed fluxes, extrapolated to 3.0–200.0 keV.

| Parameters          | MJD 53660 | MJD 53661 |
|---------------------|-----------|-----------|
| kT_{\text{disk}} (keV) | 0.53^{+0.15}_{-0.04} | 0.72^{+0.05}_{-0.04} |
| kT_e (keV)          | 6.17^{+1.84}_{-0.94} | 5.48^{+0.72}_{-0.56} |
| \tau                | 2.08^{+0.44}_{-0.42} | 2.04^{+0.24}_{-0.25} |
| \Gamma^a            | 2.71^{+0.30}_{-0.87} | 2.87^{+0.10}_{-0.15} |
| F_{\text{total}}^b (\times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}) | 3.08 | 4.43 |
| \chi^2 (d.o.f)       | 0.82 (53) | 0.74 (53) |

Notes. The best-fit model is phabs(comptt+gaussian+powerlaw), and the error bars are given at the 90% confidence level.

\textsuperscript{a} \Gamma is the power-law photon index.

\textsuperscript{b} F_{\text{total}} is the total unabsorbed flux, extrapolated to 3.0–200.0 keV.
3.3. X-ray to MIR SEDs: The Photometric Case

The first step to model the MIR emission of GRS 1915+105 was to understand in which extent the IRAC fluxes could be explained by the Rayleigh–Jeans tail of the accretion disk combined with the stellar emission. We then built the X-ray to MIR SEDs of GRS 1915+105 with the RXTE/INTEGRAL and IRAC data obtained quasi-simultaneously on MJD 53284 and MJD 53890, i.e., when the measured photometric fluxes of the source were at their lowest. Concerning the latter date, it is worth noting that about 1.2 days separate the IRAC data from the RXTE ones. Nevertheless, the light curve displayed in Figure 2 shows that between MJD 53890 and MJD 53892, the source had a steadily increasing 1.2–12.0 keV X-ray emission (with no flares) and that the disk parameters were therefore barely variable.

For each SED, the dereddened fluxes were stored in an ASCII file. They were then fitted along with the quasi-simultaneous high-energy data into an ISIS file. They were then fitted along with the quasi-simultaneous variable.

1. First, the temperature was allowed to vary between 2800 and 5000 K, which is the temperature scale of K/M giant stars (see, e.g., van Belle et al. 1999). We obtained good fits, but for temperatures that systematically pegged at the minimum allowed and for stellar radii clustered in the range 38–77/R\(_{\odot}\) depending on the considered distance. This is very unlikely because a giant star with such a low temperature would rather have a radius R\(_*\) ≥ 150/R\(_{\odot}\) (Dumm & Schild 1998; van Belle et al. 1999).

2. Second, the star’s temperature and radius were fixed to those of a K2 giant star, i.e., 4520 K and 21 R\(_{\odot}\) as given in van Belle et al. (1999), and the source’s distance was allowed to vary between 6 and 12 kpc. In both cases, the best fits, obtained for a distance of 6 kpc, were unable to completely reproduce the IRAC fluxes as there always was a MIR excess (see the fits displayed in Figure 3).

We then conclude that even when it is at its lowest, and in absence of any radio activity, the MIR emission of GRS 1915+105 cannot be explained only by the companion star and Rayleigh–Jeans tail of the accretion disk. Moreover, on MJDS 53500 and MJDS 53676, the IRAC fluxes of the source almost doubled compared to their lowest values. It is impossible that this increase comes from the companion star. On the contrary, the disk dominates the 3.0–200.0 keV unabsorbed X-ray emission, which was not the case on MJDS 53284 and MJDS 53890 (Table 3). This therefore suggests a relation between the MIR and the disk activities of GRS 1915+105.

4. ORIGIN OF THE MIR EXCESS OF GRS 1915+105

Although we excluded contributions from the companion star and the compact jets, the MIR excess we detected as well as the increase of the MIR fluxes of GRS 1915+105 may still be explained by (1) the presence of a dust component, maybe heated by the companion star and/or the X-ray/UV emission; (2) thermal bremsstrahlung from the accretion disk’s winds; (3) illumination of the accretion disk; and (4) optically thin synchrotron from a discrete ejection.

4.1. A Photoionized Dust Component?

All the IRS SL1/2 absorbed spectra of GRS 1915+105 are displayed in Figure 1, and Table 5 lists all the features we detected. All the measurements were carried out using the task IDEA of the data reduction software SMART v. 6.4.0. The central wavelength \(\lambda_{\text{fit}}\), equivalent width \(W\), FWHM, flux, and S/N of each feature were computed through Gaussian fitting. The highest source of error on the equivalent width and line flux measurement is due to the continuum, particularly uncertain at these wavelengths. Each time, instead of trying to fit it globally, the continuum was assessed in the vicinity of each feature through a linear function fitting. Several attempts showed that the resulting systematic errors were about 5% of the measured flux, which were quadratically added to the statistical uncertainties.

Along with several H\(_i\) and H\(_{\text{II}}\) emission lines that likely originate from the accretion disk, and a strong silicate absorption feature, we detected in each spectrum, except the one obtained on MJDS 53511, the so-called unidentified infrared features at 7.70 \(\mu\text{m}\) (with two primary components at 7.60 and 7.80 \(\mu\text{m}\)) and 11.25 \(\mu\text{m}\) (detected between 11.20 and 11.30 \(\mu\text{m}\)). These lines are thought to be created by the family of the polycyclic aromatic hydrocarbon molecules (PAHs; Leger & Puget 1984; Puget et al. 1985; Allamandola et al. 1985), which are found in the MIR spectra of many objects with associated dust and gas components illuminated by UV photons.
The presence of such features in the MIR spectrum of GRS 1915+105 infers that there is dust in the system. Moreover, despite the strong uncertainties, all the PAH lines appear to be strongly variable in flux; this might be related to the photoionization state of the environment of GRS 1915+105. Indeed, the excitation mode of PAH molecules is vibrational; the 7.70 μm photoionization degree (see, e.g., Allamandola et al. 1989 and Tielens 2008 for comprehensive reviews on PAH properties).

The companion star of GRS 1915+105 is a late K giant. If its emission can heat up a potential dust component, it is impossible that it photoionizes it as it is too cold to emit enough energetic UV photons. Therefore, only the X-ray emission can be responsible for the photoionization of the PAH molecules. To validate this hypothesis, we compared, for each spectrum, the evolution of the \( F_{7.7}/F_{11.3} \) PAH flux ratio with the corresponding 1.2–12.0 keV X-ray flux of GRS 1915+105. The result is displayed in Figure 4. Despite the strong uncertainties due to the silicate absorption, it suggests a correlation; the dust may therefore be photoionized by the X-ray/UV photons originated from the accretion disk and/or the corona. This would partly explain why no PAH molecules are detected in the GRS 1915+105 MIR spectrum obtained on MJD 53511. Indeed, an [Ne ii] emission feature is present at 12.81 μm. The Ne atom ionization potential is about 21.56 eV, while the PAH one is smaller than 10 eV, depending on the molecule size (Ruitenberg et al. 2005). The absence of the 11.25 μm PAH feature could consequently mean that almost all the PAHs were photoionized. But this spectrum also displays a huge increase of the continuum below about 9.00 μm, reaching the flux level measured through photometry on MJD 53500, i.e., about 8.00 mJy and 5.00 mJy at
5.80 µm and 8.00 µm, respectively. The reason for this increase will be discussed in the next section, but the non-detection of the PAH feature at 7.70 µm could be due to a contamination by the continuum, as the peak flux of the feature appears to be less than 6.00 mJy in all the other spectra where it is detected.

4.2. Effect of the Thermal Bremsstrahlung

Thermal bremsstrahlung from an expanding wind might be partially responsible for the MIR emission of GRS 1915+105. Indeed, Begelman et al. (1983) showed that X-ray driven winds could form above an accretion disk heated by X-ray radiation with luminosity a few percent above the Eddington limit, which is likely the case of GRS 1915+105, as Lee et al. (2002), and more recently Neilson & Lee (2009) and Ueda et al. (2009), detected such a wind in the system.

Thermal bremsstrahlung was already invoked by van Paradijs et al. (1994) to explain the strong MIR excess of GRO J0422+32. In their paper, they used the formalism given in Rybicki & Lightman (1979) to assess the expected 10.80 µm luminosity of a spherical expanding wind. We followed the same steps, for a disk wind emitted in a solid angle Ω, to assess the expected monochromatic luminosity of GRS 1915+105 due to free–free emission at 8.00 µm. In such a wind, the mass-loss rate $\dot{M}_w$ is

$$\dot{M}_w = \left( \frac{\Omega}{4\pi} \right) \times 4\pi r^2 m_p n_e v_w,$$

where $r$ is the distance within the wind, $m_p$ the proton mass, $n_e$ the electron density, and $v_w$ the wind velocity. Following Rybicki & Lightman (1979), the thermal bremsstrahlung emissivity at the frequency $\nu$ can be written as

$$\epsilon_\nu = 6.80 \times 10^{-45} \left( \frac{n_e^2}{\sqrt{\nu}} \right) e^{-\frac{mu}{k_B T}} \times g \ \text{W cm}^{-3} \text{Hz}^{-1},$$

where $T$ is the wind temperature, $g$ the Gaunt factor, and $h$ and $k_B$ the Planck and Boltzmann’s constants, respectively. In the following, we fix $g$ to 1, corresponding to a large angle regime in the interaction between an electron and an ion.

Replacing $n_e$ from Equation (1) into Equation (2) and integrating $\epsilon_\nu$ over the radial distance $r$ between the launching radius $R_0$ (in cm) and infinity, we obtained the monochromatic luminosity $L_\nu$ at the frequency $\nu$:

$$L_\nu = \left( \frac{\Omega}{4\pi} \right) \int_{R_0}^{\infty} \epsilon_\nu \times 4\pi r^2 dr$$

$$= 2.04 \times 10^8 \frac{e^{-\frac{mu}{k_B T}} \dot{M}_w^2}{\sqrt{T}} \left( \frac{\Omega}{4\pi} \right) v_w^2 R_0 \ \text{W Hz}^{-1}. \quad (4)$$

Following Ueda et al. (2009), we can approximate the mass-loss rate $\dot{M}_w$ as

$$\dot{M}_w \approx 1.00 \times 10^{11} \left( \frac{\Omega}{4\pi} \right) v_w \ \text{kg s}^{-1} \quad (5)$$

which in turn gives the following expression for the monochromatic luminosity:

$$L_\nu = 2.04 \times 10^{30} \left( \frac{\Omega}{4\pi} \right) e^{-\frac{mu}{k_B T}} \left( \frac{\dot{M}_w}{R_0 v_w} \right) \ \text{W Hz}^{-1}.$$  

In their thermally-driven wind model, Begelman et al. (1983) introduced four important parameters, the Compton temperature $T_C$, where heating from Compton scattering and cooling from inverse Compton are balanced out, the Compton radius $R_C$, for which the escape velocity equals the isothermal sound speed at the Compton temperature, the critical luminosity $L_{cr}$, above which a Compton heating disk wind can overcome gravity, and $T_{ch}$, which is the characteristic temperature of a parcel of gas that rises at a height $R_0$ above the disk in a finite heating time. Those parameters are defined as

$$T_C = \frac{1}{4k_B} \int_{\nu_1}^{\nu_2} h\nu L_\nu d\nu \ \text{K} \quad (7)$$

$$R_C = \frac{9.80 \times 10^{17} M_X}{T_C} \ \text{M}_\odot \ \text{cm} \quad (8)$$

$$L_{cr} \approx 2.88 \times 10^2 \frac{L_E}{\sqrt{T_C}} \quad (9)$$

$$T_{ch} = T_C \left( \frac{L}{L_{cr}} \right)^{\frac{1}{2}} \left( \frac{R_0}{R_C} \right)^{-\frac{1}{2}}, \quad (10)$$

where $M_X$ is the black hole’s mass, $L$ the X-ray bolometric luminosity, and $L_E$ the Eddington luminosity. On MJD 53284, using the continuum parameters given in Table 3 and integrating the system’s monochromatic luminosity between 1.0 and 1000.0 keV, we find $T_C \approx 5.80 \times 10^6$ K, which leads to $R_C \approx 2.37 \times 10^{12}$ cm, $L_{cr} \approx 0.12 \times L_E$, and $L \approx 0.37 \times L_E$.

Begelman et al. (1983) and Woods et al. (1996) showed that a disk wind could develop for $R_0 \geq 0.2 \times R_C$ and would get strong for $R_0 \geq R_C$. It is reasonable to assert that the thermal bremsstrahlung arises from the gravity-free part of the wind, in which $T \approx T_{ch} \approx T_C$. Then, considering $L \approx 3 \times L_{cr}$, Equation (10) leads to $R_0 \geq 3 \times R_C$. Replacing $T$ by $T_C$ and $R_0$ by $3 \times R_C$ in Equation (6), the inferred luminosity at 8.00 µm, $L_8$ is

$$L_8 \approx 1.19 \times 10^{14} \left( \frac{\Omega}{4\pi} \right) \ \text{W Hz}^{-1}.$$  

![Figure 4](image-url)
On MJD 53284, the unabsorbed luminosity of GRS 1915+105 at 8.00 μm is about (8.27 ± 1.30) × 10^{13} W Hz^{-1}. With a covering factor of about 5%, as measured for GRS 1915+105 in Neilsen & Lee (2009), we deduce a bremsstrahlung-induced luminosity at 8.00 μm of about (5.60±0.55) × 10^{12} W Hz^{-1}, which is an order of magnitude lower than what we measured. Even for a larger value of the covering factor as high as 0.2 (Proga et al. 2000), we derive about (2.38 ± 0.23) × 10^{13} W Hz^{-1}, which is still too low. It is therefore very likely that thermal bremsstrahlung from the accretion disk wind barely contributes to the MIR flux of GRS 1915+105. Moreover, Figure 1 shows that on MJD 53511, the MIR continuum of the source below about 9 μm increased while it remained almost the same beyond. Yet, the spectral signature of free–free emission is a power law with an index from 0 (optically thin) to 2 (optically thick; Wright & Barlow 1975), the wind being in the optically thin regime in the infrared. An increase of the MIR flux due to bremsstrahlung would be detected at all wavelengths, which then excludes it as a reason for the MIR brightening.

4.3. X-ray to MIR SEDs: Irradiation of the Disk

In the soft state, reprocessing—in the outer disk—of X-ray and UV photons originated from the inner part likely dominates the UV and optical emission of microquasars (Vrtilek et al. 1990; Fukue 1992; Sanbuichi et al. 1993; van Paradijs & McClintock 1994; Hynes et al. 1998, 2002; Esin et al. 2000). In the hard state, there might also be a contribution of the reprocessed hard X-ray photons from the corona. Indeed, Ueda et al. (2002) showed that it could even represent about 20%–30% of the K-band emission of GRS 1915+105 in the plateau state.

We showed that the sharp increase of the MIR emission on MJD 53511—only detected below about 9.00 μm—was not due to thermal bremsstrahlung. Dust heating is also little plausible as the MIR increase would have been detected at all wavelengths. On the contrary, it seems rather consistent with irradiation of the outer disk and/or optically thin synchrotron from a discrete ejection. To confirm this hypothesis, we built—for MJD 53284, MJD 53511, and MJD 53851—the X-ray to radio SEDs of GRS 1915+105, including the dereddened MIR spectra. Moreover, on MJD 53284 and MJD 53851, GRS 1915+105 was not detected in the radio domain so we did not include any radio flux in these SEDs.

The way we built the MJD 53511 radio to X-ray SED of GRS 1915+105 deserves some justifications. In the high energy domain, we used the MJD 53500 RXTE data because we did not have any high-energy observations quasi-simultaneous with the IRS ones (see Table 1). Indeed, the ASM fluxes and C/A HR being similar at both dates (see Figure 5), it is likely that the disk parameters were the same. Moreover, to compensate the lack of data in the radio domain, we made use of the archival Very Large Array (VLA) fluxes of the source obtained on MJD 53513 at 8.46, 14.94, and 22.46 GHz (37.90, 23.20, and 16.20 mJy respectively, about 10% uncertainties).\(^8\) At this epoch, GRS 1915+105 was in the decaying phase of a giant ejection, and the VLA flux at 14.94 GHz is similar to the ones from the Ryle telescope on MJD 53510 and MJD 53512, proving that the unknown MJD 53511 radio fluxes are barely different from the VLA ones.

The model chosen to take the reprocessing into account is diskir (Gierliński et al. 2008, 2009). Roughly, it is an extension of diskbb that includes disk irradiation (both from the inner region and the corona) as well as comptonization (based on nthcomp). The model has nine parameters: the disk’s temperature $kT_{\text{disk}}$ and norm $N_{\text{disk}}$ (same as diskbb), the hard X-rays power law $F$ and temperature $kT_e$, the ratio between the corona’s and the disk’s luminosity $L_c/L_d$, the fraction of hard X-ray emission that illuminates the disk $f_{\text{in}}$, the irradiated radius $R_{\text{irr}}$, expressed in terms of the disk inner radius, the fraction of soft X-ray emission which is thermalized in the outer disk $f_{\text{out}}$, and the logarithm of the outer radius $\log R_\text{out}$ expressed in function of the inner radius. The first seven parameters are completely defined by the high-energy data while the two latter are characterized by the optical and infrared ones.

diskir was additively combined to a Gaussian accounting for the iron feature at 6.4 keV (0.8 keV frozen width), and we fitted all the data, in ISIS, in three steps.

1. We first modified the model with a photo–electric absorption $\text{phabs} (N_H = 3.5 \times 10^{22} \text{ atoms cm}^{-2})$ and fitted the high-energy data only. The electron temperature was frozen to the value found in the previous fits with $\text{comptt}$ (see Table 3), the irradiated radius was frozen to 1.1 × $R_\text{in}$ after several unsuccessful attempts that showed that it was poorly constrained, $f_{\text{in}}$ was fixed to 0.1 for the corona-dominated spectrum and to 0.3 for the disk-dominated one (for a fixed 0.1 disk’s albedo, Poutanen et al. 1997; Ibragimov et al. 2005; Gilfanov 2010), and $f_{\text{out}}$ and $\log R_\text{out}$ were frozen to 0 and 3, respectively, as the X-ray data do not allow to constrain them.

2. We built the new radio to X-ray SEDs with the unabsorbed MIR spectra—stored in ASCII files—the RXTE data sets and the VLA radio fluxes (MJD 53511 only).

3. We finally fitted the global SEDs with the previous model combined to spherical black body component accounting for the companion star emission, another one accounting for the detected dust emission and a power law for the radio emission (MJD 53511 only). All the parameters were allowed to vary freely, except the stellar ones (temperature and radius fixed to 4520 K and 21 $R_\odot$, respectively), $kT_{\text{disk}}$ and $R_{\text{irr}}$ (same values as in step 1), and $\log R_\text{out}$ which was frozen to 0.52 $a$ (Chaty et al. 2003), $a$ being the orbital separation derived from the third Kepler’s law for a 30.8 day orbital period (Neil et al. 2007), and a 14 $M_\odot$ and 0.86 $M_\odot$ black hole and companion star, respectively (Harlaftis & Greiner 2004). Note that $\log R_\text{out}$ was dynamically tied to $R_\text{in}$ for a 10 kpc distance and a 66° inclination.

\[^8\] http://www.aoc.nrao.edu/~mrupen/XRT/GRS1915+105/grs1915+105.shtml
PCA+HEXTE and IRS data, as well as archival VLA data in the case of MJD 53511, and fitted with the model $\text{phabs(diskir+gaussian+bbodyrad+bbodyrad+powerlaw)}$.

The best-fit model is $f = T^h L_c/L_d r_{\text{out}}/L_d^{1/2} \approx 0.75 +0.05$, and the error bars are given at the 90% confidence level. The SEDs were built with the MJD 53280, MJD 53511, and MJD 53851 RXTE/PCA+HEXTE and IRS data, as well as archival VLA data in the case of MJD 53511.

All the best-fit parameters are listed in Table 6, and the fitted SEDs are displayed in Figure 6. The lack of optical and NIR data, but they show that the emission level given in the $K$ band by the irradiation component is not inconsistent with the measurements at the same epoch.

5. DISCUSSION

5.1. Origin of the Dust Component

Our results suggest the existence of a cold dust component ($T_{\text{dust}} \approx 300$–$500$ K) in the vicinity of GRS 1915+105 that likely interacts with the high-energy emission of the black hole binary. Moreover, the dust’s temperature and radius appear to be roughly constant whatever the level of the X-ray emission, which implies that the dust is heated by the K giant companion star rather than the high-energy photons. And lastly, the average dust extension derived from the fits, $R_{\text{dust}} \approx 500$ R$_\odot$ or $3.5 \times 10^{13}$ cm, is roughly 5 times larger than the orbital separation and 10 times larger than the outer radius of the accretion disk, which means that the MIR emission due to the dust is produced well beyond the binary orbit and that the dust enshrouds the whole system.

Many red giant stars are known to be embedded in a dusty shell that originates from the slow and dense stellar winds (see, e.g., Hagen 1978; Zuckerman & Dyck 1986; Morris 1987; van Loon et al. 2005), and this might be the case of the companion star of GRS 1915+105. To check the consistency of the dust’s temperature derived from the fits with the dusty stellar winds hypothesis, we can use the simple relation giving the expected temperature of a spherical dust shell in a thermodynamic equilibrium with a central star. Following Rahoui et al. (2009), this temperature is

$$T_{\text{dust}} = \left[ \frac{\pi^4}{60Q_0} \right] \left( \frac{h}{k} \right)^n \frac{1}{\Gamma(4+n)\zeta(4+n)} \left( \frac{R_s}{R_{\text{dust}}} \right)^2 T_\star^{4+n}$$

where $h$ and $k$ are the Planck and the Boltzmann constants, $\Gamma$, the gamma and $\zeta$ the Riemann zeta functions, and $Q_0$ and $n$ such as the chromatic grain emissivity $Q_v$ is defined as $Q_v = Q_0 v^n$. Typical values for carbonaceous dust are $n = 1.2$ and $Q_0 = 1.52 \times 10^{-3} r_g$, where $r_g$ is the average dust grain’s radius (see, e.g., Draine & Lee 1984; Robberto & Herbst 1998). For 0.01 $\mu$m $\leq r_g \leq 0.1$ $\mu$m, as observed for interstellar dust grains (Draine & Lee 1984), $T_\star = 4500$ K, $R_s = 21$ R$_\odot$, and $R_{\text{dust}} \approx 500$ R$_\odot$, the inferred dust temperatures is about $315$ K $\leq T_{\text{dust}} \leq 490$ K, which is consistent with our fits.

However, the dust could also originate from a dusty disk-like circumstellar component. Such disks have already been invoked...
around some isolated first-ascent red giant stars, and a possible explanation for their presence could be the engulfment of an hypothetic low-mass companion when the star entered into the red giant phase (see, e.g., Jura 2003; Jura et al. 2006; Melis et al. 2009). They also have been detected around cataclysmic variables (Dubus et al. 2004; Howell et al. 2006; Brinkworth et al. 2007; Hoard et al. 2009), and Munu & Mauerhan (2006) suggested their presence around A0620–00 and XTE J1118+480 to explain the 8.00 μm MIR excess in the emission of both sources while in quiescence. The two most common accepted explanations for the presence of circumbinary disks (CBDs) are (1) the dust was ejected from the binary with angular momentum during the common envelope phase and (2) it comes from a supernova fallback, as it was recently argued for the anomalous X-ray pulsar 4U 0142+61 (Wang et al. 2006).

In the case of a flat and optically thick CBD irradiated by the companion star, the expected temperature at a radius r is (Chiang & Goldreich 1997)

\[ T_{CBD}(r) \approx \left( \frac{2}{3\pi} \right)^{\frac{1}{2}} \left( \frac{R_c}{r} \right)^{\frac{3}{2}} T_\star. \]  

For a CBD whose inner parts are truncated by tidal forces, the expected minimum inner radius is about \( r_m \approx 1.7a \), where a is the binary separation (Artymowicz & Lubow 1994). In the case of GRS 1915+105, this leads to a maximum inner radius temperature of an hypothetical flat and optically thick CBD of \( T_{CBD}(r_m) \approx 620K \), which again is consistent with the MIR excess due to dust that we detected.

At this point, our data do not allow us to discriminate between a spherical and a disk geometry, but simple considerations confirm the presence of dust heated by the companion star and enshrouding the black hole binary. Moreover, it is worth noting that the MIR spectra of GRS 1915+105 are strongly similar in shape to those of some pre-main sequence or Herbig Ae/Be stars, silicate absorption and PAH features included (see, e.g., van Boekel et al. 2004; Sloan et al. 2005; Boersma et al. 2009; and Berné et al. 2009 for such spectra). Such stars are known to exhibit an MIR excess due to the presence of an equatorial dusty disk within which PAH molecules are photoionized by the UV emission of the central star, and we suggest that this similarity strengthens the disk scenario for the dust distribution around GRS 1915+105.

Finally, the silicate absorption feature due to the diffuse interstellar medium is strongly correlated to the optical extinction as \( A_V = (18.5 \pm 2) \times 10^{-7} \) (Draine 2003), where \( 10^{-7} \) is the optical depth of the silicate absorption at 9.70 μm. Following Chiar et al. (2007), we took \( 10^{-7} = -\ln(F_{9.7}/F_{continuum}) \), where \( F_{9.7} \) and \( F_{continuum} \) are the source and continuum’s fluxes at 9.70 μm, respectively. The optical depth was computed on the spectrum obtained on MJD 53851, as this is the one for which X-ray reprocessing has the smallest contribution in the MIR. The continuum was fitted using the ranges 5.20–7.00 μm and 13.00–14.50 μm (in order to exclude the contribution of the silicate absorption feature) with a second order polynomial. This method is strongly uncertain, especially concerning the continuum fitting, and the result should therefore be considered with caution. We nevertheless infer \( A_V = 20.04 \pm 4.13 \), which is consistent with the value found by Chapuis & Corbel (2004) for the optical extinction in the line of sight of GRS 1915+105. We therefore conclude that the silicate absorption feature in the MIR spectrum of GRS 1915+105 is likely due to the diffuse interstellar medium.

### 5.2. Importance of Irradiation

The results of the fitting of the three SEDs displayed in Figure 6 suggest that not only X-ray irradiation of the disk dominates the UV to NIR emission of GRS 1915+105, but that it also extends to the MIR, where it is overcome by the dust component between about 6 and 10 μm, depending on the accretion disk’s flux. In the thermal state (MJD 53511), the MIR continuum is even strongly dominated by the thermalization in the outer region of the soft X-ray emission from the inner parts. These results might once again emphasize the peculiarity of GRS 1915+105. Indeed, only Migliari et al. (2007) previously proposed X-ray irradiation of the disk to explain the MIR emission of GRO 1655–40 in the thermal state, and van Paradijs et al. (1994) excluded it for GRO J0422+32, arguing that the accretion disk was not large enough to have outer regions sufficiently cold to emit at these wavelengths. This is not the case of GRS 1915+105 as the latter exhibits a large accretion disk, with an assessed outer radius of about 2.86 × 10^{12} cm. A strong contribution of the X-ray irradiation extending to the infrared was then expected, and Ueda et al. (2002) already argued that it was responsible for about 20%–30% of the K-band flux in the hard state, even in presence of compact jets.

Disk illumination therefore provides a consistent explanation for the variations of the MIR continuum of GRS 1915+105. A caveat nevertheless forbids definitive conclusions. Indeed, X-ray reprocessing is thought to be the dominant contribution to the UV and optical fluxes of X-ray binaries, and any model needs these information to be well constrained. Their lack in the set of data we used to fit the SEDs is then a strong limitation to our interpretation, as the process could have artificially increased the emission at these wavelengths to better fit the MIR data. So, even if the fluxes given in Neil et al. (2007) are consistent with the ones derived from our model, only the information on at least the quasi-simultaneous \( J, H, K \)-band magnitudes could strengthen our conclusions.

### 6. CONCLUSION

We presented a multi-wavelength study of GRS 1915+105 whose outcomes suggest that, in the absence of discrete or continuous ejecta, the MIR continuum of the source is mainly due to the X-ray irradiation of the accretion disk and to a photoionized dust component. This might have consequences on the interpretation of the MIR emission of microquasars in presence of compact jets. Indeed, dust might be ubiquitous around isolated compact objects and X-ray binaries because of mass transfer during the common envelope phase or material from supernova fallback. If so, compact jets could contribute less than expected at infrared wavelengths with perhaps a cutoff frequency in the millimeter domain. To confirm our results, it is therefore crucial to increase the sample of microquasars and systematically observe them through MIR spectroscopy, as this is the only way to obtain firm information on both their environment and their continuum. In particular, studying microquasars, whose variation timescales are longer than the GRS 1915+105 ones and which do not exhibit such rapid transitions between spectral states, would strongly facilitate the multi-wavelength observations and would allow to reach definitive conclusions.

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