THE ASTROPHYSICAL JOURNAL, 461:L99–L101, 1996 April 20

INFRARED SPECTROSCOPY OF THE SUPERLUMINAL GALACTIC SOURCE GRS 1915+105 DURING THE 1994 SEPTEMBER OUTBURST

A. J. CASTRO-TIRADO
Laboratorio de Astrofísica Espacial y Física Fundamental (LAEFF), INTA, P.O. Box 50727, E-28080 Madrid, Spain
T. R. GEBALLE
Joint Astronomy Centre, 660 Aohoku Place, Hilo, HI 96720
AND
N. LUND
Danish Space Research Institute, Gl. Lundtoftevej 7, DK-2800 Lyngby, Denmark
Received 1995 September 22; accepted 1996 February 7

ABSTRACT

We have obtained *K*-band IR spectra of the superluminal Galactic source GRS 1915+105 on two different dates. The second spectrum, obtained immediately after a bright X-ray outburst in 1994 September, has shown prominent H and He emission lines. The lines are not Doppler shifted, as are those observed in SS 433, suggesting that the ionized regions in the new source are not related to the twin beams of energetic particles that are believed to be responsible for the observed radio lobes. In contrast to Cygnus X-3, where the companion is likely to be a Wolf-Rayet star, we suggest that GRS 1915+105 is likely to be a low-mass X-ray binary. The IR flux probably arises from free-free emission in a wind flowing out of the accretion disk.

Subject headings: binaries: general — infrared: stars — stars: individual (GRS 1915+105) — X-rays: general

1. INTRODUCTION

X-ray transients are mainly related to X-ray binaries. Most of them are associated with soft X-ray transients, a subclass of low-mass X-ray binaries (LMXRBs) in which sporadic outbursts are produced because of a poorly understood mechanism through which mass is intermittently transferred onto a compact object via an accretion disk. The compact object is either a weakly magnetized neutron star (e.g., Cen X-4 and Aql X-1) or a black hole (e.g., A0620−00 and V404 Cyg). The duration of the transient flaring ranges from days to a few months. Shortly after the onset of the outburst, these sources become among the brightest objects in the X-ray sky (Tanaka & Lewin 1995).

The transient X-ray source GRS 1915+105 was discovered on 1992 August 15 by the WATCH all-sky X-ray monitor on the *Granat* satellite, and for a while became one of the brightest sources in the X-ray sky (Castro-Tirado, Brandt, & Lund 1992; Castro-Tirado et al. 1994). Since the very beginning, its behavior was very unusual when compared with previous X-ray transients. In fact, activity was already observed by the BATSE instrument on the *Compton Gamma Ray Observatory* (*CGRO*) as early as 1992 May (Harmon et al. 1994). Since then, several X-ray outbursts lasting a few months have been observed.

Based on an improved position given by the γ-ray SIGMA telescope on *Granat* (Finoguenov et al. 1994), a variable radio source was detected in 1992 December (Mirabel et al. 1993). Following an outburst in 1994 March, the radio lobes of the source exhibited superluminal motion, the first such case in our Galaxy (Mirabel & Rodríguez 1994).

A second source, GRO J1655−40, has recently been shown to have superluminally expanding radio jets (Hjellming & Rupen 1995; Tingay et al. 1995), and it has been proposed that both GRS 1915+105 and GRO J1655−40 constitute a very distinct subclass of X-ray transients.

GRS 1915+105 is close to the Galactic plane ($b = -0\overset{\circ}{.}22$), and its distance has been estimated to be 12 ± 2 kpc (Rodríguez et al. 1995). High optical absorption puts the source beyond the reach of any optical telescope. On 1993 July 7, IR observations revealed a highly reddened object ($J - K = 3.66$) consistent with the position of the radio source (Castro-Tirado et al. 1993), thus confirming the candidate proposed on the basis of other observations taken at La Silla 1 month earlier (Mirabel et al. 1994).

2. OBSERVATIONS AND RESULTS

We have obtained service observations at the United Kingdom 3.8 m Infrared Telescope (UKIRT) on Hawaii. A *K*-band spectrum covering 2.03–2.25 μm was obtained at UKIRT on 1993 September 28. The cooled grating spectrograph CGS4 was used, with the low-resolution grating (75 lines mm^{-1}) providing a resolving power of 650. There is no evidence for emission lines in the spectrum; a weak structure around 2.06 μm is possibly related to a moderately strong atmospheric CO_2 line that is not completely canceled. The source was found to be at a very low level of X-ray activity at that time (Sazonov et al. 1994; Harmon et al. 1994).

Following one of the above-mentioned X-ray outbursts in 1994 September (Sazonov et al. 1994; Alexandrovich, Borozdin, & Sunyaev 1994), a second *K*-band spectrum was taken on 1994 October 7, when the X-ray flux of GRS 1915+105 in the 8–20 keV band was ~0.35 crab units. Both spectra are shown in Figure 1. It can be seen that between 1993 September and 1994 October the continuum flux density of GRS 1915+105 increased by a factor of about 2. This increase was accompanied by the appearance in the spectrum of prominent emission lines characteristic of ionized gas. For each of the lines, the identification, observed flux, equivalent width, and full width at half-maximum are given in Table 1.

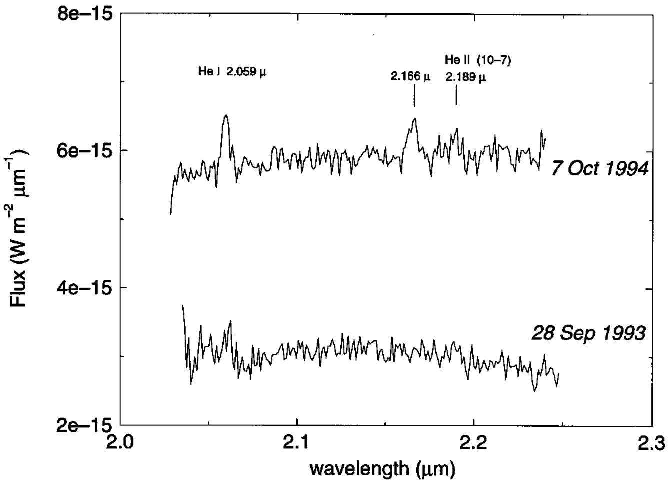

FIG. 1.—*K*-band spectra of GRS 1915+105, obtained at UKIRT on 1993 September 28 and 1994 October 7. Shown are the reduced spectra, flux-calibrated using the spectra from HR 7377. Line identifications are shown.

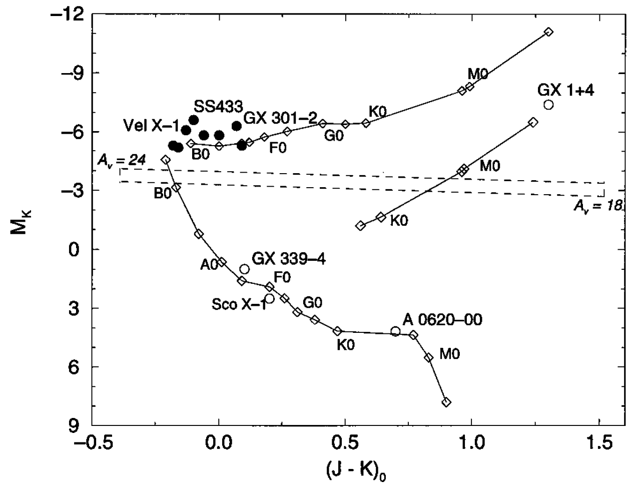

FIG. 2.—Infrared (2.2 μm) Hertzsprung-Russell diagram for $J-K$ colors of Galactic X-ray binaries. Filled circles represent HMXRBs, and open circles LMXRBs. The dashed line includes the possible sites for the companion of GRS 1915+105, assuming $D = 12 \pm 2$ kpc and $K = 14.3$ (Mirabel et al. 1994) for the system in quiescence, i.e., that the light arises mostly from the companion. Note that a HMXRB can be excluded.

3. DISCUSSION

The spectral lines observed in GRS 1915+105 are not Doppler shifted, as they are in the case of SS 433 (Margon 1988). The absence of P Cygni profiles and the smaller widths of the lines than observed toward Wolf-Rayet (W-R) stars (Conti, Massey, & Vreux 1990; Smith & Hummer 1988) and toward Cygnus X-3 (with its possible WN7 companion; van Kerkwijk et al. 1992) indicate that an ultra–high-velocity wind is not present in the system. This result, together with the fainter than expected *K* magnitude of the W-R stars (Lumsden, Puxley, & Doherty 1994), rules out such an object as the optical companion of GRS 1915+105.

We have constructed an IR Hertzsprung-Russell diagram based on $J-K$ colors, in which we have represented the Galactic X-ray sources (Fig. 2). Although the distance to GRS 1915+105 seems to be established as 12 ± 2 kpc (Rodríguez et al. 1995), the value of the visual extinction toward the source is not yet clarified. A lower limit can be inferred from the observed column density along the line of sight to the object, from which a value of 2×10^{22} cm^{-2} is given for molecular hydrogen (Durouchoux 1994), plus an additional column density of atomic hydrogen of $\sim 2 \times 10^{22}$ cm^{-2} (Mirabel & Rodríguez 1994). The total value, $N_{\rm H} \sim 4 \times 10^{22}$ cm^{-2}, is compatible with the absorption column derived from the low-energy cutoff of the X-ray flux, implying values from 4.3×10^{22} to 5×10^{22} cm^{-2} (Greiner et al. 1993; Nagase et al. 1994). Using the relationship between the optical extinction A_v and $N_{\rm H}$ (Gorenstein 1975), we found that A_V is probably in the range 18–24 mag. According to the diagram, we can rule out GRS 1915+105 being a high-mass X-ray binary (HMXRB), in contrast to SS 433 or Cygnus X-3, and conclude that GRS 1915+105 is likely to be an LMXRB.

TABLE 1

EMISSION LINES OBSERVED IN GRS 1915+105

Line	λ (μm)	Line Flux[a]	−EW[b]	FWHM[c]
He I	2.060 (1)	3.9 (1)	7.0 (5)	7.3 (2)
H I Brγ	2.166 (1)	3.4 (1)	6.0 (5)	8.9 (3)
He II	2.189 (1)	1.8 (2)	3.5 (5)	7.5 (7)

[a] In 10^{-18} W m^{-2}. In all cases, errors indicate 90% confidence limits.
[b] EW is the equivalent width in angstroms.
[c] FWHM is the observed full width at half-maximum in 10^2 km s^{-1}.

The idea of GRS 1915+105 as a LMXRB is also supported by its X-ray behavior. Several years prior to the discovery, the region was observed by the *Einstein* satellite, but no source was detected at the position of GRS 1915+105, implying a large difference in flux ($\sim 4 \times 10^3$) from 1979 to 1992 (Castro-Tirado 1994). A similar limit was obtained by *ROSAT* in 1990 (Greiner et al. 1993). Moreover, GRS 1915+105 displayed initially a hard spectrum, followed by a gradual softening. All these characteristics are reminiscent of soft X-ray transients (Mineshige et al. 1992; Sunyaev et al. 1994).

The continuum IR flux probably arises from free-free emission in a wind flowing out of the accretion disk, as has been already proposed for two soft X-ray transients, A0620−00 (Glass 1994; Oke & Greenstein 1977) and GRO J0422+32 (van Paradijs et al. 1994). This wind would be formed (Begelman, McKee, & Shields 1983) by X-ray heating of the disk if the X-ray luminosity exceeded a few percent of the Eddington limiting luminosity $L_{\rm Edd} \sim 1.3 \times 10^{38}$ $(M/M_\odot)$ ergs s^{-1}. This probably happened in GRS 1915+105 during the 1994 September outburst. Extrapolating the spectrum seen by *ASCA* on 1994 September 28 (Nagase et al. 1994) to higher energies, $L_{\rm X} \sim 5 \times 10^{38}$ ergs s^{-1} (Sazonov et al. 1994), yields a value larger than $\sim 2 \times 10^{38}$ ergs s^{-1}, the Eddington luminosity for a canonical 1.4 $M_\odot$ neutron star.

The strength of the 2 ^1P–2 ^1S He I line at 2.058 μm may be a result of multiple resonant scattering of 584 Å photons, indicating the presence near the object of a high-density region, possibly the accretion disk with a high He abundance (derived from the He I/Brγ line ratio) where the emission lines such as those seen in the GRS 1915+105 IR spectrum can arise. The He line will also be pumped by the strong UV continuum flux produced by the reprocessing of X-rays in the disk. For case B recombination (Glass 1994; Osterbrock 1989), and using the Balmer-to-Brackett ratios, the number of ionizing photons, $Q({\rm H}^0)$, can be derived from the luminosity of the Brγ line, as $7.6 \times 10^{13} L_{{\rm Br}\gamma}$. For a distance of $\sim$12 kpc,

$L_{Br\gamma} = 7.2 \times 10^{32}$ ergs s^{-1} and $Q(H^0) = 5.4 \times 10^{46}$ photons s^{-1}. The detection of the He II line at 2.189 μm indicates that the temperature of this emission region is $(3-4) \times 10^4$ K.

There is a long debate (Kouveliotou et al. 1993; Grindlay 1994; Mirabel & Rodríguez 1995) about the possibility of GRS 1915+105 as the origin of the soft δ-ray repeater SGR 1900+14, discovered by KONUS (Mazets et al. 1981) in 1979. However, no X-ray source comparable to GRS 1915+105 was revealed at the time of the bursts in 1979 by the *Vela* and *Einstein* satellites (Castro-Tirado 1996). We conclude that, with the available data, we probably have to await a new episode of bursting activity from the source responsible for the *Konus* event to finally settle this issue. Spectroscopic observations are needed as well, in order to distinguish whether the compact object in the GRS 1915+105 is a neutron star or a black hole.

We are very grateful to M. Cerviño, M. Mas-Hesse, and S. Brandt for very fruitful discussions. We thank R. Gershberg, L. Pavlenko, S. Guziy, A. Shlyapnikov, I. Marquez, M. Moles, J. L. Ortiz, H. U. Norgaard-Nielsen, R. F. Nielsen, J. Davies, C. Everall, J. L. Sanz, N. Benítez, and E. Martínez for the CCD frames taken at different epochs during their respective observing times. We also thank S. Sazonov and W. Paciesas for valuable information about WATCH and BATSE results. UKIRT is operated by the Carnegie Observatories, on behalf of the UK Particle Physics and Astronomy Council.

REFERENCES

Alexandrovich, N., Borozdin, K., & Sunyaev, R. 1994, IAU Circ., No. 6080

Begelman, M. C., McKee, C. F., & Shields, G. A. 1983, ApJ, 271, 70

Castro-Tirado, A. J. 1994, Ph.D. thesis, Univ. Copenhagen

———. 1996, in AIP Conf. Proc., 3d Huntsville Symp. on Gamma-Ray Bursts, ed. C. Kouvelioton, M. S. Briggs, & G. J. Fishman (New York: AIP), in press

Castro-Tirado, A. J., Brandt, S., & Lund, N. 1992, IAU Circ., No. 5590

Castro-Tirado, A. J., Brandt, S., Lund, N., Lapshov, I., Sunyaev, R. A., Shlyapnikov, A. A., Guziy, S., & Pavlenko, E. P. 1994, ApJS, 92, 469

Castro-Tirado, A. J., Davies, J., Brandt, S., & Lund, N. 1993, IAU Circ., No. 5830

Conti, P. S., Massey, P., & Vreux, J. M. 1990, ApJ, 354, 359

Durouchoux, P., et al. 1994, IAU Circ., No. 6000

Finoguenov, A., et al. 1994, ApJ, 424, 940

Glass, I. 1994, MNRAS, 268, 742

Gorenstein, P. 1975, ApJ, 198, 95

Greiner, J., et al. 1994, in AIP Conf. Proc. 304, Second *Compton Gamma-Ray Observatory* Symposium, ed. C. E. Fichtel, N. Gehrels, & J. P. Norris (New York: AIP), 260

Grindlay, J. E. 1994, ApJS, 92, 465

Harmon, B. A., et al. 1994, in AIP Conf. Proc. 304, Second *Compton Gamma-Ray Observatory* Symposium, ed. C. E. Fichtel, N. Gehrels, & J. P. Norris (New York: AIP), 210

Hjellming, R. M., & Rupen, M. P. 1995, Nature, 375, 464

Kouveliotou, C., et al. 1993, Nature, 362, 728

Lumsden, S. L., Puxley, P. J., & Doherty, R. M. 1994, MNRAS, 268, 821

Margon, B. 1988, ARA&A, 22, 507

Mazets, E. P., et al. 1981, Ap&SS, 80, 1

Mineshige, S., et al. 1992, PASJ, 44, 117

Mirabel, I. F., et al. 1993, IAU Circ., No. 5779

———. 1994, A&A, 282, L17

Mirabel, I. F., & Rodríguez, L. F. 1994, Nature, 371, 46

———. 1995, Ap&SS, 231, 65

Nagase, F., & the *ASCA* Team. 1994, IAU Circ., No. 6094

Oke, J. B., & Greenstein, J. L. 1977, ApJ, 211, 872

Osterbrock, D. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: University Science Books)

Rodríguez, L. F., Gerard, E., Mirabel, I. F., Gómez, Y., & Velázquez, A. 1995, ApJS, 101, 173

Sazonov, S., et al. 1994, Astron. Lett., 20(6), 787

Smith, L. F., & Hummer, D. G. 1988, MNRAS, 230, 511

Sunyaev, R. A., et al. 1994, Astron. Lett., 20(6), 777

Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126

Tingay, S. J., et al. 1995, Nature, 374, 141

van Kerkwijk, M. H., et al. 1992, Nature, 355, 703

van Paradijs, J., Telesco, C. M., Kouveliotou, C., & Fishman, G. J. 1994, ApJ, 429, L19