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The binary components of GRS 1915+105

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Abstract. I summarize recent near-infrared spectroscopy of the microquasar GRS 1915+105 with the ESO/VLT which allowed to (i) identify the donor and (ii) measure the orbital period and radial velocity amplitude. Assuming that the jet ejections occur perpendicular to the accretion disk and orbital plane, the mass of the black hole is determined to $M = 14 \pm 4$ M$_\odot$. I discuss the implications of this mass determination on (a) the understanding of the large-amplitude X-ray variability in GRS 1915+105, (b) binary formation scenarios, and (c) models to explain the stable QPO frequencies in GRS 1915+105 and GRO J1655-40.

1. Introduction

GRS 1915+105 (Castro-Tirado et al. 1994) is the prototypical microquasar, a galactic X-ray binary ejecting plasma clouds at v≈0.92 c (Mirabel & Rodriguez 1994). It exhibits unique X-ray variability patterns (Greiner et al. 1996) which have been interpreted as accretion disk instabilities leading to an infall of parts of the inner accretion disk (Belloni et al. 1997). Based on its X-ray properties GRS 1915+105 was suspected to be the most massive stellar black hole candidate in the Galaxy (Morgan et al. 1997). Besides GRO J1655-40, GRS 1915+105 is one of only two galactic sources which are thought to contain a maximally spinning black hole (Zhang et al. 1997). It is therefore of great importance to know some details about the system components in the GRS 1915+105 binary in order to understand the conditions which lead to the unique X-ray, radio, and infrared characteristics.

2. Observations and Results

2.1. The donor

GRS 1915+105 is located in the galactic plane at a distance of ∼11 kpc (Fender et al. 1999) and suffers extreme extinction of 25–30 mag in the visual band. We therefore obtained spectroscopic observations in the near-infrared H and K bands using the ISAAC instrument on the VLT-Antu telescope. Based on spectra taken in the 5 wavelengths bands 1.56–1.64 μm, 1.63–1.72 μm, 2.05–2.17 μm, 2.17–2.29 μm and 2.29–2.41 μm we successfully identified absorption features from the atmosphere of the companion (mass donating star) in the GRS 1915+105 binary (Greiner et al. 2001a). The detection of ^{12}CO and ^{13}CO band heads (Fig. 1) plus a few metallic absorption lines suggests a K-M spectral type and

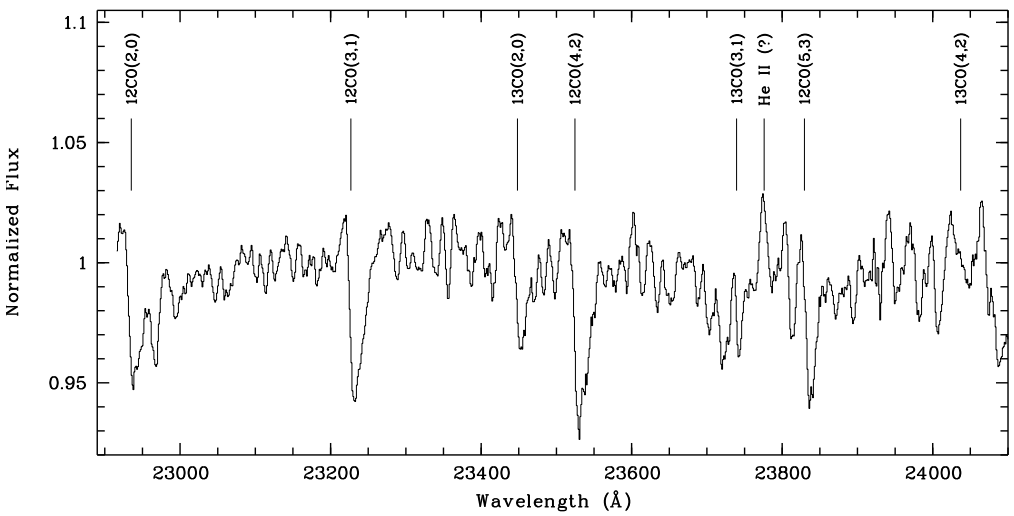

Figure 1. Mean K band spectrum of GRS 1915+105. CO bandheads are clearly discovered and marked by vertical lines. The presence of the ^{13}CO isotope and the equivalent width ratio of ^{12}CO to ^{13}CO suggests a classification of the donor as a late-type giant.

luminosity class III (giant). Comparing the equivalent widths of the ^{12}CO(3,1) ^{12}CO(4,2) and ^{12}CO(5,3) bandheads between the GRS 1915+105 spectrum and that of a K2 III standard star (observed with the same settings) implies that the donor of GRS 1915+105 has an unveiled magnitude of 14.5–15.0 mag (prior to extinction correction). This in turn implies an absolute magnitude of $M_{\rm K}$ = –2...–3, consistent with the giant classification. This K-M III classification also implies a constraint on the mass of the donor of $M_{\rm d} = 1.2 \pm 0.2$ M$_\odot$ (Greiner et al. 2001a). This proves that GRS 1915+105 is a low-mass X-ray binary (LMXB), as has been suggested earlier based on the IR spectral variability and on its position on the IR H-R diagram (Castro-Tirado et al. 1996), though the contrary claim has been made by Mirabel et al. (1997) and Martí et al. (2000) that based on the detection of He I, the donor in GRS 1915+105 should be a high-mass O or B star, and that accretion occurs predominantly from the wind of the donor.

2.2. The radial velocity curve

Subsequently, a series of medium-resolution spectra in the 2.39–2.41 μm range using the VLT-Antu equipped with ISAAC was obtained between April and August 2000 (Greiner et al. 2001b). Radial velocities were measured for the individual spectra by cross-correlation of the major CO band heads, using as template a spectrum of the K2 III star HD 202135 taken with the same setting. The results of this cross-correlation (after heliocentric correction) are shown in Fig. 2: The radial velocity periodogram shows a clear peak at a period of 33.5 days (top panel) which is interpreted as the orbital period $P_{\rm orb}$ of the binary system (Greiner et al. 2001b). All measurements, folded over this period, are shown in the lower panel of Fig. 2. The velocity amplitude is measured to be

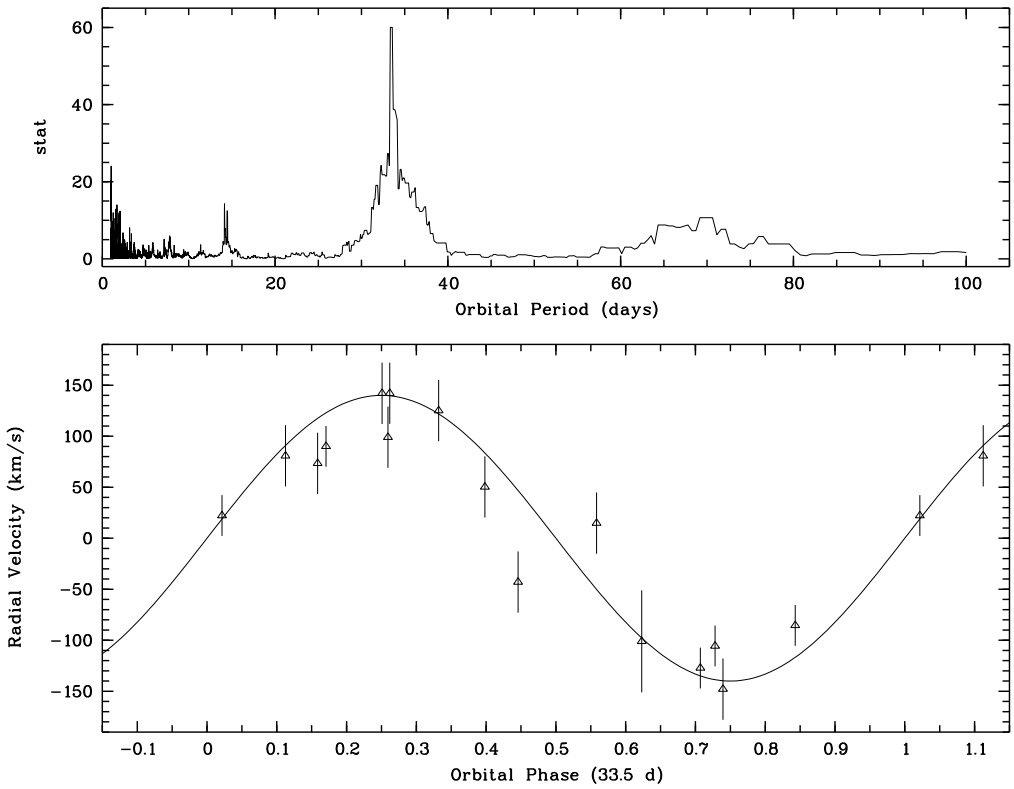

Figure 2. Result of the period analysis of the velocity variation of the four CO bandheads. **Top:** Scargle periodogram after heliocentric correction of the individual measurements. **Bottom:** Radial velocity curve folded over the best-fit period of $P_{\rm orb} = 33.5$ days. The semi-amplitude of the velocity curve $K_{\rm d}$ is 140±15 km/s (from Greiner et al. 2001b).

$K_{\rm d} = 140\pm15$ km/s. With these values, the mass function, i.e. the observational lower limit to the mass of the compact object is (Greiner et al. 2001b)

$$f(M) \equiv \frac{(M_{\rm c}\sin i)^3}{(M_{\rm c}+M_{\rm d})^2} = \frac{P_{\rm orb}\,K_{\rm d}^3}{2\,\pi\,G} = 9.5 \pm 3.0\,M_\odot. \qquad (1)$$

GRS 1915+105 has shown several major jet ejection events for which the brightness and the velocities of both the approaching and the receding blobs could be measured (Mirabel & Rodriguez 1994, Fender et al. 1999). From this, the angle of the jet axis relative to the line of sight has been determined to be $\approx 70^\circ \pm 2^\circ$ and constant over several years. With the assumption that the jet is perpendicular to the accretion disk and orbital plane, this provides a reasonably accurate measure of the inclination angle i of the binary system. Knowing the inclination i, Eq. 1 can be solved for the mass of the accreting compact object (Fig. 3), giving $M_{\rm c} = 14 \pm 4$ M$_\odot$. Table 1 summarizes the orbital parameters

Table 1. Spectroscopic Orbital Parameters of GRS 1915+105

Parameter	Result
T_0 (UT)[1]	2000 May 02 00:00
T_0 (Heliocentric)[1]	HJD 2 451 666.5±1.5
γ (km/s)	–3±10
$K_{\rm d}$ (km/s)	140±15
$P_{\rm orb}$ (days)	33.5±1.5
$f(M)$ ($M_\odot$)	9.5±3.0
$M_{\rm d}$ ($M_\odot$)	1.2±0.2
$M_{\rm c}$ ($M_\odot$)[2]	14±4

[1] Time of blue-to-red crossing. [2] Using an inclination angle of $i = 70^\circ \pm 2^\circ$ (Mirabel & Rodriguez 1994, Fender et al. 1999).

of GRS 1915+105. Even when accounting for the relatively large error (which is dominated by the error in the determination of the velocity amplitude $K_{\rm d}$), GRS 1915+105 is the galactic binary with the largest mass function and the largest mass of its compact object. Previous record holders were V404 Cyg ($f(M) = 6.07 \pm 0.05$, $M_{\rm c} = 7 - 10$ $M_\odot$; Shahbaz et al. 1996) and XTE J1118+480 ($f(M) = 6.00 \pm 0.36$, $M_{\rm c} = 6.5 - 10$ $M_\odot$; McClintock et al. 2001).

We note that given the high mass-loss of the donor (which is needed to explain the large X-ray luminosity), it is most certainly less luminous than a non-interacting star of the same spectral type (Langer et al. 2000). This implies a larger mass for the donor, thus making the above black hole mass a lower limit. While it is difficult to assess the exact impact of the mass loss on the donor mass, the very extreme and conservative case of doubling the mass is plotted in Fig. 3. This indicates that the black hole mass could be higher by 1–3 $M_\odot$ at maximum.

Distortions of the radial velocity curve due to X-ray heating (e.g. Phillips et al. 1999) are likely to be unimportant because of the long orbital period in GRS 1915+105. Using their eq. 2, one finds that the maximum possible deviation for GRS 1915+105 would be 8%, as compared to their 14% for GRO J1655-40. In analysing their data, Phillips et al. (1999) finally find that the true velocity amplitude in GRO J1655-40 is smaller than the measured one by 4.5%. Thus, one could expect a 2–3% effect in GRS 1915+105, compared to our presently given error which amounts to 11%. However, since the infrared flux contribution from the secondary star in GRS 1915+105 is so small, there is the possibility that phase-dependent changes in the continuum near the absorption features may result in an additional source of systematic error in the measured value of the velocity amplitude $K_{\rm d}$.

The systemic velocity of the GRS 1915+105 binary system is $\gamma = -3 \pm 10$ km/s which implies that based on the galactic rotation curve (Fich et al. 1989) the kinematic distance of GRS 1915+105 is $d = 12.1 \pm 0.8$ kpc, intermediate between earlier estimates (Mirabel & Rodriguez 1994, Fender et al. 1999).

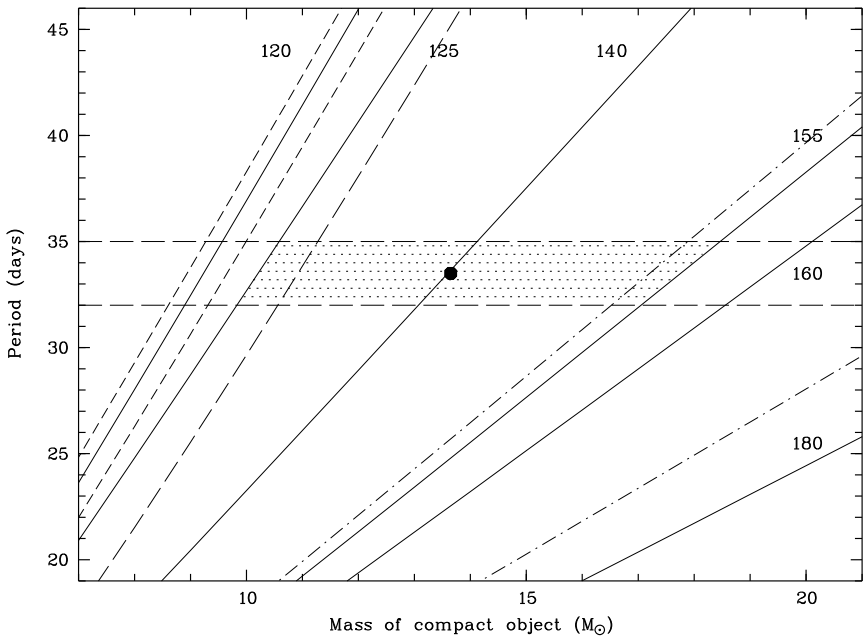

Figure 3. Constraints on the black hole mass in GRS 1915+105. The relation of orbital period versus mass of the accreting compact object is plotted for various velocity amplitudes K (solid lines, in km/s), assuming i=70° and a mass of the donor of 1.2 $M_\odot$. The dotted region shows the parameter space as constrained by the uncertainty of the period and radial velocity amplitude (125–155 km/s). The uncertainty in the mass of the donor is shown for $K = 120$ km/s where the slanted dashed lines correspond to 1.0, 1.4 and 2.5 $M_\odot$, respectively (from left to right). While the formal uncertainty in the orbital inclination is only 2°, we show the effect of relaxing the assumption of the jet being perpendicular to the orbital plane by showing for the $K = 160$ km/s case the corresponding curves using $i = 79°$ (at which angle eclipses would set in; left dash-dot curve) and $i = 61°$ (right dash-dot curve).

3. Discussion

3.1. Formation of a 14 $M_\odot$ black hole

The knowledge of the mass of the black hole in GRS 1915+105 has several implications for both the understanding of the physics in microquasars (for a review see Mirabel & Rodriguez 1998; Greiner 2000) as well as some broader astrophysical concepts. Most importantly, the formation of a 14 $M_\odot$ black hole in a low-mass binary poses an interesting challenge for binary evolution. Stellar evolution of stars in a binary system proceeds differently from single star evolution due to primarily the mass transfer between the system components and/or common-envelope phases. There are, in general, two different paths for the black hole formation in a binary system. First, the progenitor system could

be wide, and during the common envelope phase the low-mass (main sequence) star of $\sim$1 $M_\odot$ will spiral into the envelope of the massive giant (progenitor of the black hole), causing the orbit to shrink (Kalogera 1999, 2001). Based on the measured system parameters (Tab. 1), the deduced orbital separation of the binary components in GRS 1915+105 is $a = 108\pm4$ $R_\odot$. Thus, orbital contraction through a common-envelope phase caused by the expansion of the massive progenitor to typically $\gtrsim$1000 $R_\odot$, is conceivable for GRS 1915+105. Second, the evolution could start with a progenitor system smaller than today, provided that the binary component interaction is delayed until after He burning has ceased (Brown et al. 1999). In this case, the time between the wind phase and the core-collapse is short, and black hole masses in the 5–10 $M_\odot$ range have been reproduced for cases where the initial He-star progenitor is in the 10–25 $M_\odot$ range, corresponding to initial primaries in the 25–45 $M_\odot$ range (Brown et al. 2001, Kalogera 2001). How much mass is finally lost depends on the radii evolution of the two progenitor stars, and it remains to be shown whether black hole masses above 10 $M_\odot$ can be achieved.

In order to produce BH masses $\gtrsim$10 $M_\odot$, the progenitor might have been a massive Wolf-Rayet star. However, Wolf-Rayet stars are known to have a much larger wind-loss rate, and it is therefore unclear whether higher progenitor masses indeed will lead to higher final black hole masses. Also, the effects of rapid rotation on the mass loss become more serious. Even if one assumes no mass-loss at all from the helium star, the predicted masses for helium cores of massive stars can not account for BH masses $\gtrsim$12–14 $M_\odot$ (Wellstein & Langer 1999, Hurley et al. 2000). An alternative possibility to produce high-mass ($\gtrsim$10 $M_\odot$) black holes may be to invoke hierarchical triples as progenitors (Eggleton & Verbunt 1986).

Whatever the formation path may be, it seems that the mass of the black hole in the binary GRS 1915+105 may provide the impetus to study the formation of black holes with masses above 10 $M_\odot$ in more detail.

3.2. On the luminosity and X-ray variability of GRS 1915+105

With the values of Table 1, the implied Roche lobe size of the donor star is 21 ± 4 $R_\odot$, in good agreement with the size of a K-M giant which therefore can be expected to fill its Roche lobe. Thus, accretion in GRS 1915+105 is likely to occur via Roche lobe overflow.

The knowledge of the mass of the accretor in GRS 1915+105 also allows us to possibly understand the rapid and large-amplitude X-ray variability which is seen only in GRS 1915+105 (Greiner et al. 1996). Combining the observed X-ray intensity with the measured distance immediately shows that this large-amplitude X-ray variability occurs near or even above the Eddington limit $\dot{M}_{\rm Edd}$. Such high accretion rates are seemingly never reached by other canonical black hole transients (e.g. GRO J1655-40) which usually operate in the 0.1-0.2 $\dot{L}_{\rm Edd}$ range. At these lower rates the accretion disks are likely gas pressure dominated, and thus viscously and thermally stable. In contrast, the uniquely high $\dot{M}/\dot{M}_{\rm Edd}$ ratio in GRS 1915+105 suggests that its inner part of the accretion disk is radiation pressure dominated, which in turn makes the inner disk quasi-spherical and thermally unstable. This property potentially provides the clue for the spectacular and unique X-ray variability in GRS 1915+105 (Greiner et al. 1996) which

has not been found in any other X-ray binary. Indeed, under the assumptions of a corona dissipating 50% of the energy and a jet carrying a luminosity-dependent fraction of energy, Janiuk et al. (2000) show that the time-dependent behaviour of GRS 1915+105 can be well reproduced with the α-viscosity prescription in a radiation pressure dominated region.

Also, while it is tempting to conclude that jet ejection occurs because the black hole can not accept this copious supply of matter, it is important to remember that jet ejection occurs also in these other sources, at e.g. 0.2 $\dot{M}_{\rm Edd}$ in GRO J1655-40, and thus near/super-Eddington accretion cannot be the determining factor for relativistic jets.

3.3. On the black hole spin in GRS 1915+105 and GRO J1655-40

The knowledge of the black hole mass also allows us to place constraints on the question of the black hole spin in GRS 1915+105 and GRO J1655-40. Information on the black hole spin in both sources has been deduced from two completely different sources: (1) Accretion disks around a (prograd) spinning black hole extend farther down towards the black hole, and thus allow the temperature of the disk to be higher. Since both GRS 1915+105 and GRO J1655-40 exhibit a thermal component in their X-ray spectra which has an unprecedently high temperature as compared to all other black hole transients (during outbursts), it has been argued that this is due to the spin of the black holes in these two sources, while the majority of black hole transients has non-rotating black holes (Zhang et al. 1997). (2) Several black hole binaries, including GRS 1915+105 and GRO J1655-40, show nearly-stable quasi-periodic oscillations (QPO) in their X-ray emission. The frequencies f for these QPOs are 300 Hz in GRO J1655-40 (Remillard et al. 1999) and 67 Hz in GRS 1915+105 (Morgan et al. 1997). Very recently, a related second stable QPO has been discovered for each of these (Strohmayer 2001a,b). Most of the models proposed to explain these QPO either rely or depend on the spin of the accreting black hole.

If the black hole mass in GRS 1915+105 is indeed no larger than 18 $M_\odot$ (Fig. 3), the deduction of the black hole spin by Zhang et al. (1997) is inconsistent to any of the four models on the origin of QPOs:

1. If associated with the Keplerian motion at the last stable orbit around a (non-rotating) black hole according to the simple relation f (kHz)= $2.2/M_{\rm BH}$ ($M_\odot$), it gives a surprising agreement with the optically determined mass for GRO J1655-40 of 7 $M_\odot$ (Orosz & Bailyn 1997), but is off by a factor of 2 for GRS 1915+105.
2. If associated with the trapped g-mode (diskoseismic) oscillations near the inner edge of the accretion disk (Okazaki et al. 1987, Perez et al. 1997, Nowak et al. 1997) would give consistency for a nearly maximally spinning black hole in GRO J1655-40, and a non-spinning black hole in GRS 1915+105, contrary to the argument that the spin in both systems should be very similar because of the extremely high temperature of the accretion disk (Zhang et al. 1997).
3. If associated with the relativistic dragging of inertial frames around a spinning black hole (Cui et al. 1998) which would cause the accretion disk to precess, the implied specific angular momentum (spin) of the black hole in GRS 1915+105 would be $a \sim 0.8$, thus considerably lower than the

$a \sim 0.95$ deduced for GRO J1655-40. This is in conflict with the nearly identical accretion disk temperatures for both sources as deduced from the X-ray spectra, which in turn requires a larger spin for GRS 1915+105.

4. If associated with oscillations related to a centrifugal barrier in the inner part of the accretion disk (Titarchuk et al. 1998), the product of QPO frequency and black hole mass is predicted to be proportional to the accretion rate, implying that the accretion rate in GRO J1655-40 should be a factor $\sim$10 larger than in GRS 1915+105. This is certainly not the case, since the black hole mass in GRO J1655-40 is about 7 $M_\odot$ (Orosz & Bailyn 1997).

A different phrasing of the above item (1) is that one cannot argue that based on the QPO frequency difference the mass of the black hole in GRS 1915+105 should be a factor of 4–5 larger than that in GRO J1655-40. This relation would only hold for the assumption that the QPO frequencies are correlated to the Kepler frequency. Our mass determination shows that the QPO frequency does *not* scale linearly with the mass of the black hole. As a consequence, their origin is very likely *not* related to the Keplerian frequency.

Thus, none of these four models provides a satisfactory solution if one adopts the interpretation that the high accretion disk temperatures are a measure of the black hole spin (Zhang et al. 1997). If, on the contrary, this latter interpretation is dropped, and the spin becomes a free parameter, the first three models could be applicable.

It should be noted that the applicability of the applied standard Shakura-Sunyaev disk model to deduce accurate accretion disk temperatures has been also questioned on other grounds (Sobczak et al. 1999, Merloni et al. 2000). In addition, there also exist alternative models, so-called slim disk models, which can reproduce high-temperature disks also for non-rotating black holes (see review by Balbus & Hawley, or a recent application by Watarai et al. 2000).

3.4. Other implications

Besides the above issues there are a number of other implications of the high value of the black hole mass in GRS 1915+105 which are summarized below: (1) It proves beyond doubt (and beyond any details in nuclear matter physics which occasionally argue even about 7 $M_\odot$ neutron stars; see e.g. Negi & Durgapal 2001) the existence of stellar black holes. (2) It has been argued that the compact objects in most black-hole transients cluster around 7 $M_\odot$ (Bailyn et al. 1998), contrary to the expectation (assuming that the initial mass function is weighted toward lower mass stars) of a monotonic distribution of black holes biased toward lower masses. The mass of GRS 1915+105 adds to the hints (based on V404 Cyg and Cyg X-1) that there is a range of black hole masses in binaries, though the bias towards low masses (3-5 $M_\odot$) still remains to be clarified. (3) It invalidates the counter-argument against these $\sim$7 $M_\odot$ black holes being neutron stars plus a self-gravitating, 5 $M_\odot$ accretion disk (Kundt 1999). An accretion disk with a mass of $\sim$13 $M_\odot$ seems impossible, both because of the higher mass-transfer which would have to last many Myrs, as well as the unstable location of the neutron star within the disk.

Whatever the solutions to the individual implications may be, the microquasar GRS 1915+105 continues to surprise scientists with unforeseen challenges, and to be among the most exciting X-ray sources on the sky.

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