An unusually massive stellar black hole in the Galaxy

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GRS 1915+105 belongs to the small group of galactic X-ray binaries dubbed microquasars [1, 2], which show sporadic ejection of matter at apparently superluminal speeds. Knowing the basic system parameters of GRS 1915+105 is not only a prerequisite of understanding the ingredients of jet formation, but also provides the link to many other astrophysical objects which exhibit jets, in particular extragalactic objects. Based on its large X-ray luminosity during high-states of $7 \times 10^{39}$ erg/s [3] and the interpretation of the X-ray timing properties [4], a mass of $\sim 10-30$ M$_\odot$ has been suggested for the accreting compact object in GRS 1915+105. It is also one of only two galactic binary sources which are thought to contain a maximally spinning black hole [5]. Here we report a measurement of the orbital period and
mass function of GRS 1915+105 which allow us to deduce a mass of $14 \pm 4 \, M_\odot$ for its black hole. This large mass provides a challenge for the black hole formation scenarios in binaries, since black holes with masses above $5–7 \, M_\odot$ are hard to explain [6, 7, 8, 9]. Also, the mass estimate allows us to understand the unique X-ray variability of GRS 1915+105 as being due to instabilities of a radiation-pressure dominated disk radiating near the Eddington limit. Finally, several models are constrained which relate observable X-ray properties to the spin of black holes in microquasars. Once further calibrated, these relations may soon turn into a valuable tool to study relativistic effects in strong gravitational fields.

GRS 1915+105 is located in the galactic plane at a distance of $\sim 11–12 \, kpc$ [10, 11] and suffers a large extinction of 25–30 mag in the visual band. Spectroscopic observations in the near-infrared H and K bands were successful in identifying absorption features from the atmosphere of the companion (mass donating star) in the GRS 1915+105 binary [12], and the detection of $^{12}$CO and $^{13}$CO band heads plus a few metallic absorption lines suggested a K-M spectral type and luminosity class III (giant).

The presence of these band-head features led us to carry out follow-up medium-resolution spectroscopy in the 2.39–2.41 $\mu$m wavelength range using the VLT-Antu
equipped with ISAAC, between April and August 2000 (Fig. 1). Radial velocities were measured for the 16 individual spectra by cross-correlation of the major CO band heads, and a period analysis carried out (Fig. 2). The periodogram shows a clear peak at a period of 33.5 days (top panel) which we interpret as the orbital period $P_{\text{orb}}$ of the binary system. The velocity amplitude is measured to be $K_d = 140 \pm 15$ km/s (lower panel). Figure 1 shows that the infrared flux is dominated by light from the accretion flow or jet, rather than from the secondary star. There is thus a 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 $K_d$. The measured parameters allow us to determine the mass function $f(M)$, i.e. the observational lower limit to the mass of the compact object

$$f(M) \equiv \frac{(M_c \sin i)^3}{(M_c + M_d)^2} = \frac{P_{\text{orb}} K_d^3}{2 \pi G} = 9.5 \pm 3.0 \, M_\odot.$$  \hspace{1cm} (1)

In order to determine the true mass of the black hole, estimates of the donor mass $M_d$ and the orbital inclination $i$ are required. The K-M III classification, at first approximation, implies a mass of $M_d = 1.2 \pm 0.2 \, M_\odot$ for the donor [12]. Because of the high mass-loss of the donor (which is needed to explain the large X-ray luminosity), the donor is most certainly less luminous than a non-interacting star of the same spectral type. This in turn would imply a larger donor mass, thus making the black hole mass
estimate (see below) a lower limit when using \( M_d = 1.2 \, M_\odot \). The orbital inclination of the GRS 1915+105 binary can be deduced from the orientation of the jet, which in turn is derived from the brightness and the velocities of both the approaching and the receding blobs [11, 10]. This angle of \( \approx 70^\circ \pm 2^\circ \) was observed to be constant over several years, indicating no measurable precession, and justifies us assuming that the jet is perpendicular to the accretion disk and orbital plane. Thus, knowing the inclination \( i \) and a lower limit of the donor mass, we can solve Eq. 1 for the mass of the accreting compact object (Fig. 3), finding \( M_c = 14 \pm 4 \, M_\odot \). Table 1 summarises all orbital parameters of GRS 1915+105. Even after accounting for the relatively large error dominated by the determination of the velocity amplitude \( K_d \), GRS 1915+105 is the galactic low-mass X-ray binary with the largest mass function and the largest mass of its compact object. Previous record holders were V404 Cyg \((f(M) = 6.07 \pm 0.05, M_c = 7 - 10 \, M_\odot \, [13])\) and XTE J1118+480 \((f(M) = 6.00 \pm 0.36, M_c = 6.5 - 10 \, M_\odot \, [14])\).

The knowledge of the mass of the black hole in GRS 1915+105 has several implications for our understanding of the physics in microquasars, 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 models. Stellar evolution of stars in a binary system proceeds differently from single star evolution.
primarily due to 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 \cite{9, 15}. Based on our measured system parameters (Table 1), the deduced orbital separation of the binary components in GRS 1915+105 is $108 \pm 4 \, R_\odot$. 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 the binary component interaction is delayed until after He burning has ceased \cite{8}. 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 are plausible when the initial He-star progenitor is in the 10–25 $M_\odot$ range, corresponding to initial primaries with 25–45 $M_\odot$ \cite{8, 9}. How much mass is finally lost depends on the evolution of the two progenitor star radii, and it remains to be shown whether black hole masses above 10 $M_\odot$ can be achieved. In order to produce even higher black hole masses, the progenitor might have been a massive Wolf-Rayet star. However, Wolf-Rayet stars 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. An alternative way of producing high-mass ($\gtrsim 10 \, M_\odot$) black holes may be to invoke hierarchical triples as progenitors [16].

Turning to the details of accretion disk physics and microquasar phenomenology, the knowledge of the mass of the accretor in GRS 1915+105 also yields insight into the rapid and large-amplitude X-ray variability seen uniquely in this source [17], and which occurs near or even above the Eddington limit $\dot{M}_{\text{Edd}}$. Such high accretion rates are never reached by other canonical black hole transients (e.g. GRO J1655-40) which usually operate in the 0.1-0.2 $\dot{L}_{\text{Edd}}$ range, at which their accretion disks are likely gas pressure dominated, and thus viscously and thermally stable. The uniquely high $\dot{M}/\dot{M}_{\text{Edd}}$ ratio in GRS 1915+105 suggests that its inner accretion disk is radiation pressure dominated, which in turn makes the inner disk quasi-spherical and thermally unstable. This property provides a potential clue for the spectacular and unique X-ray variability in GRS 1915+105 [17]. 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, (e.g. at $0.2 \dot{M}_{\text{Edd}}$ in GRO J1655-40), and thus near/super-Eddington accretion cannot be the determining factor for relativistic jets.

Finally, if the black hole mass in GRS 1915+105 is indeed no larger than 18 $M_\odot$ (Fig. 3), we can place constraints on the black hole spin in GRS 1915+105 and GRO
J1655-40. Previously, information on the black hole spin has been deduced from two completely different sources. First, accretion disks around a (prograde) 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 is unprecedently high compared to all other black hole transients (during outbursts), it has been argued that this is due to their black hole spin, while the majority of black hole transients have non-rotating black holes. Second, several black hole binaries, including GRS 1915+105 and GRO J1655-40, show nearly-stable quasi-periodic oscillations (QPOs) in their X-ray emission. The frequencies $f$ for these QPOs are 300 Hz in GRO J1655-40 and 67 Hz in GRS 1915+105. Most of the models proposed to explain these QPOs either rely or depend on the spin of the accreting black hole. The knowledge of the black hole mass of GRS 1915+105 makes the deduction of the black hole spin of inconsistent with any of these 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) = $2.2/M_{\text{BH}}$ (M$_\odot$), it gives a surprising agreement with the optically determined mass for GRO J1655-40, but is off by a factor of 2 for GRS 1915+105, i.e. the QPO frequency does not scale linearly with the mass of the black hole. (2) If associated with the trapped g-mode (diskoseismic) oscillations near the inner edge of the accretion
disk \([19, 20]\) would require a nearly maximally spinning black hole in GRO J1655-40, and a non-spinning black hole in GRS 1915+105. (3) Similarly, if associated with the relativistic dragging of inertial frames around a spinning black hole \([21]\) 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. The implications of both of these models are in conflict with the nearly identical accretion disk temperatures for both sources which in turn requires a larger spin for GRS 1915+105 \([5]\). (4) If associated with oscillations related to a centrifugal barrier in the inner part of the accretion disk \([22]\), 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.

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 \([3]\). If this latter interpretation is dropped, however, and the spin becomes a free parameter, the first three models could be applicable. It should be noted that the applicability of the applied disk model to deduce accurate accretion disk temperatures has been also questioned on other grounds \([23, 24]\), and that there also exist alternative models, so-called slim disk models, which can reproduce high-temperature disks also
for non-rotating black holes [23].

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Acknowledgements: This work is based on observations collected at the European Southern Observatory, Chile under proposal ESO No. 65.H-0422.
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                        |
| $\gamma$ (km/s)                   | −3±10                                       |
| $K_d$ (km/s)                       | 140±15                                      |
| $P_{orb}$ (days)                   | 33.5±1.5                                    |
| $f(M)$ ($M_\odot$)                | 9.5±3.0                                     |
| $M_d$ ($M_\odot$)                  | 1.2±0.2                                     |
| $M_c$ ($M_\odot$)$^{(2)}$         | 14±4                                        |

$^{(1)}$ Time of blue-to-red crossing.

$^{(2)}$ Using an inclination angle of $i = 70±2$ degrees [11, 10] (see caption of Fig. 3).
Figure 1: Mean K band spectrum of GRS 1915+105. It was obtained at the ESO VLT-Antu telescope, using the short wavelength (0.9–2.5 μm) arm of ISAAC, equipped with a 1024×1024 pixel Rockwell HgCdTe array with an image scale of 0′′147/pixel. Using the medium resolution grating (1.2 Å/pixel in the K band) yields a spectral resolution of ∼3000 with a 1″ slit. Science exposures of GRS 1915+105 consisted of eight 250 sec individual exposures which were dithered along the slit by ±10″. In order to correct for atmospheric absorption, the nearby star HD 179913 (A0 V) was observed either before or after each science exposure. The initial data reduction steps like bias subtraction, flatfielding and co-adding were performed within the Eclipse package [27]. The extraction and wavelength calibration was done using an optimal extraction routine within the MIDAS package. The spectrum shown here is the sum of 5 exposures with 167 min. total integration time. 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. The observed small width and faintness of the CO bandheads imply that the donor contributes only
Figure 2: Result of the period analysis of the velocity variation of the four CO bandheads. Radial velocities were measured for the individual spectra by cross-correlation of the major CO band heads, using as template a spectrum of the K2III star HD 202135 taken with the same setting. **Top:** Scargle periodogram after heliocentric correction of the individual measurements. **Bottom:** Radial velocity curve folded over the best-fit period of $P_{\text{orb}} = 33.5$ days. The semi-amplitude of the velocity curve $K_d$ is $140 \pm 15 \text{ km/s}$. Distortions of the radial velocity curve due to X-ray heating (e.g. [28]) to be unimportant because of the long orbital period. The systemic velocity is $\gamma = -3 \pm 10 \text{ km/s}$ which implies that based on the galactic rotation curve [20] the kinematic distance of GRS 1915+105 is $d = 12.1 \pm 0.8 \text{ kpc}$, intermediate between earlier estimates [11, 10].
Figure 3: Black hole mass constraints for GRS 1915+105. The relation of orbital period versus mass of the black hole is plotted for various velocity amplitudes \( K \) (solid lines, in km/s). We assumed an orbital inclination of 70° and a mass of the donor of 1.2 M\(_\odot\). The horizontal long-dashed lines indicated the boundaries of the period uncertainty, and the radial velocity range is 125–155 km/s. Thus, the dotted region shows the parameter space, leading to a mass of the accreting compact object of 14±4 M\(_\odot\). 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 thus is very likely to fill its Roche lobe. The uncertainty in the mass of the donor is shown for \( K = 120 \text{ km/s} \) 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 \( K = 160 \text{ km/s} \) 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). Thus, when relaxing the assumptions and using the extremes, the mass range would be 8–24 M\(_\odot\). \(^{17}\)