On the Mass-Donating Star in GRS 1915+105

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ABSTRACT

We present an analysis of constraints on the companion mass for the Galactic microquasar GRS 1915+105. Using the known inclination angle and stability of the jet axis, we can rule out massive ($M_s \gtrsim 3M_\odot$) companions with orbital axes not aligned with the jet axis. For an aligned orbital axis, we constrain the ratio of the stellar radius to the binary semi-major axis to be $R_s/a < 0.342$, based on the lack of X-ray eclipses. We then show that these constraints together with the X-ray luminosity, approximate black hole mass, and observations of the X-ray absorbing column density towards GRS 1915+105 rule out accretion via stellar wind from a massive companion, implying that accretion occurs via Roche-lobe overflow. In that case, the constraint on R_s/a rules out any companion with $M_s > 19.4M_\odot$ for a black hole mass of $M_{BH} \simeq 30M_\odot$. The lack of significant X-ray reprocessing in the infrared from GRS 1915+105 also provides constraints on the mass and temperature range of a Roche-lobe-filling mass donor.

Subject headings: infrared: stars – Xrays: stars – black hole physics – stars: individual: GRS 1915+105 – binaries:close

1. Introduction

As the first Galactic source of superluminal jets, GRS 1915+105 has undergone intensive study during recent years. Despite this level of investigation, one of the system's key parameters – the approximate mass of the mass-donating star in the binary – remains a subject of controversy. No binary modulation in the system, such as eclipses, have been observed at any wavelength, preventing insights based on orbital properties and evolution. Mirabel et al., (1997) observed near-infrared emission lines of He I and Brγ, which they interpreted as evidence for a massive Oe- or Be-type companion star. However, Castro-Tirado et al. (1996) and Eikenberry et al. (1998) reported the observation of a weak, time-variable He II emission line (later confirmed by Marti et al., 2000). Since normal Oe and Be stars do not typically doubly-ionize He, they suggested that the emission lines arise in the accretion disk surrounding the compact object, leaving the companion star type unconstrained. Furthermore, Eikenberry et al. (1998) observed the emission lines changing in strength by factors of several on timescales of $\sim 5 - 10$ minutes during jet-producing activity. They interpreted the constancy of the line profiles during these rapid changes as further evidence of the accretion disk origin of the lines.

More recently, Marti et al. (2000) have presented VLT spectra of GRS 1915+105, in which they confirm the weak He II emission line and identify another emission line due to NaI (2.21μm). They interpret this feature as evidence that the mass-donating star in GRS 1915+105 is a super-massive star, such as a luminous blue variable (LBV) star. However, they note that this interpretation does not seem able to explain the line variability observed by Eikenberry et al. (1998).

In this paper, we will also address the nature of the mass-donating star. Based on the known inclination angle of the jet axis, its stability over timescales of years, and the lack of X-ray eclipses in GRS 1915+105, we place constraints on the ratio of the mass-donating star's radius R_s to the semi-major axis of the binary system a. We then show, based on estimates of the black hole mass in GRS 1915+105, its X-ray luminosity, and the observed X-ray absorption column towards GRS 1915+105, that the accretion in the system cannot be provided by the wind of a massive star. We then show that for a $30M_{\odot}$ black hole undergoing accretion via Roche lobe overflow, the mass-donating star is constrained to have $M_s < 19.4M_{\odot}$. Next, we use limits on X-ray reprocessing on the stellar surface to place further constraints on the mass-donating star. Finally, we discuss the implications of these results for GRS 1915+105 and present our conclusions.

2. Geometry of GRS 1915+105

In the paper announcing the discovery of superluminal motion from GRS 1915+105, Mirabel & Rodriguez (1994) were able to constrain the inclination angle of the jet axis to be $\theta = 70^{\circ} \pm 2^{\circ}$. Furthermore, in the observed jet outbursts since then, this angle has remained stable to within a few degrees on timescales of years (e.g. Fender et al., 1999). Thus, the orbital motion of the compact object does not significantly alter the direction of the jet axis. This constancy can be provided by one of two possibilites: either the mass ratio of the system is small ($q = M_s/M_{BH} \ll 1$), or else the orbital axis is aligned with the jet axis. The first case in and of itself strongly constrains the nature of the companion star. In the second case, further analysis is required to see if the nature of the companion star can be constrained.

The first component in this analysis is the lack of X-ray eclipses in GRS 1915+105. This object has been monitored by the Rossi X-ray Timing Explorer (RXTE) All-Sky Monitor since early 1996, and with a huge number of pointed observations using the RXTE Proportional Counter Array (e.g. Muno et al., 2000). It has also been extensively studied using ASCA (e.g. Kotani et al., 2000), BeppoSAX (e.g. Feroci et al., 2000), Granat-Sigma

(Castro-Tirado, et al., 1994), and the Compton Gamma-Ray Observatory (e.g. Harmon, et al., 1997). Despite this wealth of coverage, no X-ray eclipse has ever been observed from GRS 1915+105. For an orbit aligned with the jet axis at $\theta = 70$ degrees, this constrains the ratio of the star radius to the orbital separation to be

$$\frac{R_s}{a} \leq \cos(70^\circ) = 0.342$$

3. Accretion via Stellar Wind

3.1. Limits on $\dot{M}$ and the Stellar Wind

If the mass-donating star in GRS 1915+105 is in fact an early-type star, one possibility for providing the accreted mass is through a stellar wind. The accretion rate must be able to account for the high X-ray luminosity observed from GRS 1915+105, with $L_x \simeq 3 \times 10^{39}$ ergs s^{-1} (e.g. Belloni et al., 1997). If we assume a canonical efficiency of 15% for converting accreted mass into radiated energy (e.g. Frank et al., 1992), we arrive at an accretion rate of $\dot{M} \simeq 3 \times 10^{-7}\ M_\odot$ yr^{-1}.

Wind accretion is known to be rather inefficent compared to Roche lobe overflow – only the wind material directed towards the compact object is accreted. More quantitatively, the accretion rate from the wind $\dot{M}_{wind}$ is related to the stellar mass loss rate $\dot{M}_s$ according to

$$\dot{M}_{wind} \simeq {}^1\!/_4\ \dot{M}_s\ q^{-2}\ (R_s/a)^2$$

The mass of the black hole in GRS 1915+105 is not well-determined. However, Zhang, et al. (1997) and Nowak, et al. (1997) suggest $M_{BH} \sim 30 M_\odot$ based on the 67 Hz quasi-periodic oscillation observed from the system (Morgan et al., 1997). Furthermore, by requiring the peak X-ray luminosity to be less than the Eddington luminosity, we find $M_{BH} > 23M_\odot$ – consistent with the result of Zhang, et al. (1997). Therefore, we adopt $M_{BH} = 30M_\odot$ here. For a super-massive star as suggested by Marti et al., we have $M_s \gtrsim 50M_\odot$ (Humphreys & Davidson, 1994), giving $q \gtrsim 1.6$. For an accretion rate $\dot{M} \geq 3 \times 10^{-7} M_\odot$ yr^{-1}, we then arrive at $\dot{M}_s \gtrsim 2.7 \times 10^{-5} M_\odot$ yr^{-1}. This mass-loss rate is very high – even the LBV stars have an upper end to their mass loss between outbursts of $\sim 10^{-5} M_\odot$ yr^{-1} (e.g. Davidson & Humphreys, 1997). Since GRS 1915+105 has shown repeated patterns of X-ray emission over timescales of several years, implying steady accretion over this interval as compared to the variable aperiodic outflows typical of LBV stars in outburst (e.g. Humphreys & Davidson, 1994), it seems likely that any LBV-type mass-donating star is not in outburst. Thus, the wind mass-loss rate required to produce the observed X-ray emission is marginally consistent with the mass-loss rates known to occur in such stars.

The required wind mass-loss rate decreases with decreasing q until $q \simeq \frac{R_s}{a} = 0.34$, at which point essentially all of the stellar wind not initially flowing away from the compact object is captured. For $q = 0.34$, we have $\dot{M}_s \gtrsim 1.2 \times 10^{-6} M_\odot$ yr^{-1} for a $\sim 10M_\odot$ star. This mass-loss rate is again consistent with the rates inferred for the O/B companions in wind-fed high-mass X-ray binaries (e.g. Frank et al., 1992), though this stellar mass range is at the lower limit for such stars.

3.2. Limits from X-ray Absorption

The tremendous stellar wind required to provide the X-ray luminosity of GRS 1915+105 should also have an impact on the observed absorbing column density towards the X-ray source. Given a minimum stellar mass-loss rate from above and the wind velocity v_{wind}, we can place a lower limit on the wind density as a function of distance from the star's center r according to

$$\rho(r) = \frac{\dot{M}_s}{4\pi r^2\ v_{wind}}$$

We take $v_{wind} = 10^3$ km s^{-1} here – somewhat larger than typical for these systems, making the above density a firm lower limit.

For this minimum $\dot{M}_s$, the ratio R_s/a is fixed at 0.342. Furthermore, for supermassive LBV stars, an upper limit on their size is $R_s \lesssim 1$ AU, giving an upper limit on the orbital separation of $a_{max} = 2.9$ AU. For a less-massive O/B-type star, we have $R_s \lesssim 0.1$ AU, giving $a_{max} = 0.29$ AU. Given these system parameters and assuming a uniform spherical wind, we can calculate the line-of-sight column density through the wind for an observer at a 20° angle above the orbital plane. It is important to note that the assumption of uniform spherical outflow is not generally critical for the results of this calculation. Rather, we only require that the line of sight sample the typical density regimes of any more-complicated outflow – a requirement that will be satisfied for all but the most contrived geometries in this case. Based on this, we estimate the lower limit to the column density to be $n_H \gtrsim 1.5 \times 10^{23}$ cm^{-2} for an LBV-type star and $n_H \gtrsim 7 \times 10^{22}$ cm^{-2} for an O/B-type star when the mass-donating star lies between the observer and the X-ray source.

For comparison, the measured total column density towards GRS 1915+105 is $n_H \simeq 6 \times 10^{22}$ cm^{-2} (e.g. Belloni et al., 1997)[4], and the vast majority of this absorption is attributable to the intervening ISM (Chaty, et al., 1996). Furthermore, as the orbital orientation changes, any wind-induced absorption column would vary systematically,

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[4] This measurement assumes solar abundances. For enriched winds (commonly seen in these stars), the apparent absorption would be even higher, increasing the contrast between observations and the wind-accretion model.

dropping by a factor of > 5 at opposition – see Figure 1. However, spectra collected over long time intervals show no such variability in absorption for GRS 1915+105(e.g. Muno et al., 1999). So, even the lowest estimates for stellar winds capable of providing the accreting matter produce X-ray absorption greatly in excess of that observed. Therefore, we conclude that a stellar wind cannot provide the accretion observed in GRS 1915+105.

4. Accretion via Roche-lobe Overflow

4.1. Maximum stellar mass

Roche-lobe overflow is generally a much more efficient mode of mass-transfer than stellar winds, with essentially all of the mass-loss transferring onto the compact object. Thus, we have $\dot{M}_s \simeq 3 \times 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. Moreover, as Eggleton (1983) has shown, Roche lobe overflow requires that the mass ratio q and the ratio of the stellar radius to the binary separation follow

$$\frac{R_s}{a} = \frac{0.49\ q^{2/3}}{0.6 q^{2/3} + \ln(1 + q^{1/3})}$$

For our upper limit of $R_s/a \lesssim 0.342$ above, we arrive at an upper limit of $q \lesssim 0.647$, corresponding to a limit on the stellar mass of $M_s \lesssim 19.4 M_\odot$ (assuming $M_{BH} = 30 M_\odot$). This upper limit is more than a factor of 2 below the *lower* limit for supermassive stars of the type suggested by Marti et al. (2000) as the companion for GRS 1915+105.

4.2. Limits from X-ray reprocessing

We can also place limits on Roche-lobe-filling companion stars to GRS 1915+105 due to the apparent lack of significant infrared (IR) flux from reprocessed X-rays in the system

(Eikenberry et al., 2000). They place limits on the IR flux density due to reprocessing of $\Delta F_\nu < 3 \times 10^{-26}$ ergs s^{-1} cm^{-2} Hz^{-1} at $\nu = 1.4 \times 10^{14}$ Hz (2.2μm), in the presence of $\Delta L_x \simeq 10^{39}$ ergs s^{-1}. For thermal reprocessing on a blackbody of temperature T, we have a reprocessing efficiency ϵ (ratio of the bolometric reprocessed luminosity to the emitted X-ray luminosity) given by

$$\epsilon = \frac{c^2}{2\pi\nu^2}\frac{\sigma T^3}{k}\frac{\Delta L_\nu}{\Delta L_x}$$

assuming the change in temperature is small compared to the temperature ($\Delta T \ll T$), changes in the surface area of the blackbody are negligible, and $\Delta L_\nu = 4\pi d^2 \Delta F_\nu$ where we take $d = 12.5$ kpc (Mirabel & Rodriguez, 1994). From simple geometry, we can see that ϵ should also have the form

$$\epsilon = (1-\eta)\frac{\pi\ R_s^2}{4\pi\ a^2}$$

where η is the X-ray albedo of the stellar surface (assumed to be $\eta \simeq 0.5$ here – e.g. Anderson, 1981).

Given this relationship between ϵ and $\frac{R_s}{a}$ at a given temperature T and the relationship between q and $\frac{R_s}{a}$ for Roche-lobe overflow, we can then calculate an upper limit on q as a function of stellar surface temperature. Figure 2 shows a plot of the parameter space (mass, temperature) allowed/excluded for Roche-lobe-filling stars[5] (assuming $M_{BH} = 30M_\odot$).

One important consideration here is that we have ignored the possible effects of the

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[5] Note that for stars with $M_s \lesssim 3M_\odot$ ($q \lesssim 0.1$), the constraint on the alignment of the orbital axis with the jet axis may be relaxed, so that the stellar temperature is not constrained by this method.

accretion disk casting an X-ray shadow on the star, thus reducing the amount of reprocessing on the stellar surface. However, this intercepted radiation does not simply disappear – rather it is reprocessed on the disk itself. While the efficiency of this reprocessing depends on the temperature and albedo of the disk region intercepting the radiation, the star subtends only an azimuthal range of $\frac{2R_s}{a}$ radians as seen from the center of the accretion disk, while the disk extends a full 2π radians. Thus, if the disk intercepts any fraction of the X-ray light that would otherwise reach the star, it will in fact intercept at least $\frac{\pi a}{R_s}$ times that amount of light over its total azimuthal range. Given our limit of $\frac{R_s}{a} < 0.342$, this means that as long as the disk reprocessing efficiency is at least 10% of the stellar reprocessing efficiency per unit area, any disk shadowing would actually *increase* the total amount of reprocessed light over the above estimate, and thus tighten the constraint given the upper limits on reprocessed radiation. Therefore, we consider the constraints in Figure 2 to be fairly robust against the effects of disk shadowing.

5. Discussion

5.1. The companion star mass

As shown above, any reasonable parameters for accretion via stellar wind produce large X-ray absorption which is inconsistent with observations of GRS 1915+105. Furthermore, for accretion via Roche-lobe overflow, we can rule out any star with $M_s > 25 M_\odot$ as well as all but the hottest stars with $M_s \gtrsim 3 M_\odot$. Thus, a super-massive companion, as suggested by Marti et al. (2000), does not seem possible for GRS 1915+105.

The likeliest "normal" candidates for the mass-donating star are either a main-sequence or giant (luminosity class III) early-B star, or a low-mass ($M_s \lesssim 3 M_\odot$) star. For the expected stellar radii and masses of massive stars and assuming accretion via Roche lobe overflow, we would then expect binary periods for massive donor stars in GRS 1915+105 to range over $\sim 10 - 15$ days. For low-mass companions, the range of expected binary periods is very poorly constrained.

Given the $\dot{M} \geq 3 \times 10^{-7} M_{\odot}$ yr^{-1} accretion rate required to produce the X-ray luminosity, one might expect a low-mass star to imply a short lifetime for the "active" phase of GRS 1915+105 – $\tau \sim M/\dot{M} \simeq 10^6 - 10^7$ years. However, while GRS 1915+105 has been active for most of the last 8 years, we know it was quiescent for several decades prior to this. Therefore, the duty cycle for active mass transfer in this system may be $\ll 1$, so that the lifetime can be considerably larger than the above estimate.

5.2. Whence the IR emission lines?

The primary motivation for the initial suggestion of a super-massive companion by Marti et al. (2000) was the IR emission line spectrum. The stars allowed under the above analysis could not produce sufficient ionizing radiation to explain the observed IR spectrum from GRS 1915+105. However, it is important to note that the IR lines observed from LBV and other such stars are *not* produced directly in the stellar photosphere/chromosphere. Rather, they are the result of the dense stellar wind being irradiated by UV emission from the luminous hot photosphere.

In the case of GRS 1915+105, we *know* that the system contains a hot, highly-luminous blackbody – the inner accretion disk, which we observe directly in X-rays, should also produce tremendous ionizing UV luminosity. Furthermore, the outer portions of such a disk are widely considered to be the sources of strong winds, and we are most interested in this particular system due to its strong outflows. Recent X-ray spectral analysis by Kotani et al. (2000)also indicate the presence of such a disk wind. Therefore, we hypothesize that the emission spectrum observed by Marti et al. (2000) (as well as others previous to them) derives not from a super-massive companion star, but from the accretion disk itself.

This latter explanation also fits well with the observations of Eikenberry et al. (1998). The observed rapid variability of the IR emission lines is correlated with flaring behavior in GRS 1915+105 in a manner suggesting radiative pumping. Since the line profiles are constant, the line-emitting region must be uniformly irradiated by the flares which appear to come from the inner accretion disk. This is not possible for a line emission from the envelope of a massive companion – the star itself will shield a considerable fraction of its envelope from the flare. However, if the lines arise from the disk, the line-emitting region is axisymmetric about the flaring region, guaranteeing uniform irradiation and maintaining the constancy of the emission line profiles.

5.3. The black hole mass

A key assumption for much of the above analysis is the mass of the black hole in GRS 1915+105. As noted above, both arguments based on the Eddington luminosity and (more speculative) interpretations of quasi-periodic oscillations imply $M_{BH} \simeq 30 M_{\odot}$. This estimate would make the black hole in GRS 1915+105 the most massive of the "stellar-mass" black hole candidates in the Galaxy – roughly 3 times more massive than the black hole in Cyg X-1. Based on the above arguments, $M_{BH} = 30 M_{\odot}$ eliminates the possibility of a super-massive companion star ($M_s \gtrsim 50 M_{\odot}$) as suggested by Marti et al. (2000). Furthermore, in order to allow a companion consistent with even the lowest portion of the LBV mass range would require $M_{BH} \gtrsim 75 M_{\odot}$.

6. Conclusions

We have presented an analysis of the possible companion star mass ranges for GRS 1915+105, and come to the following conclusions:

- Based on the 70° inclination angle and stability of the jet axis, we find that either the mass ratio of the system is $q \ll 1$, or the orbital axis is aligned with the jet axis.
- Based on the lack of X-ray eclipses, for massive companions ($q \gtrsim 0.1$), the radius of the star must be $R_s < 0.342a$, where a is the semi-major axis of the orbit.
- Given these constraints and the X-ray luminosity of GRS 1915+105, all reasonable parameters assuming accretion via a stellar wind produce an X-ray aborption in the wind which is incompatible with observations. This indicates that accretion must occur via Roche-lobe overflow in GRS 1915+105.
- For Roche-lobe overflow, the constraint on R_s/a requires the companion star to have $M_s < 19.4 M_\odot$ (assuming $M_{BH} = 30 M_\odot$).
- Based on limits for IR flux from reprocessed X-ray in GRS 1915+105 (Eikenberry et al., 2000), any companion star with $3M_\odot < M_s < 25M_\odot$ must have a surface temperature $T \gtrsim 1 - 2 \times 10^4$ K. The "normal" main sequence and giant stars which fall into this range are early-B stars.
- The IR emission lines do not arise in the envelope of a massive companion, but instead are likely to be produced by the outer accretion disk and/or a disk wind being irradiated by the hot inner accretion disk.

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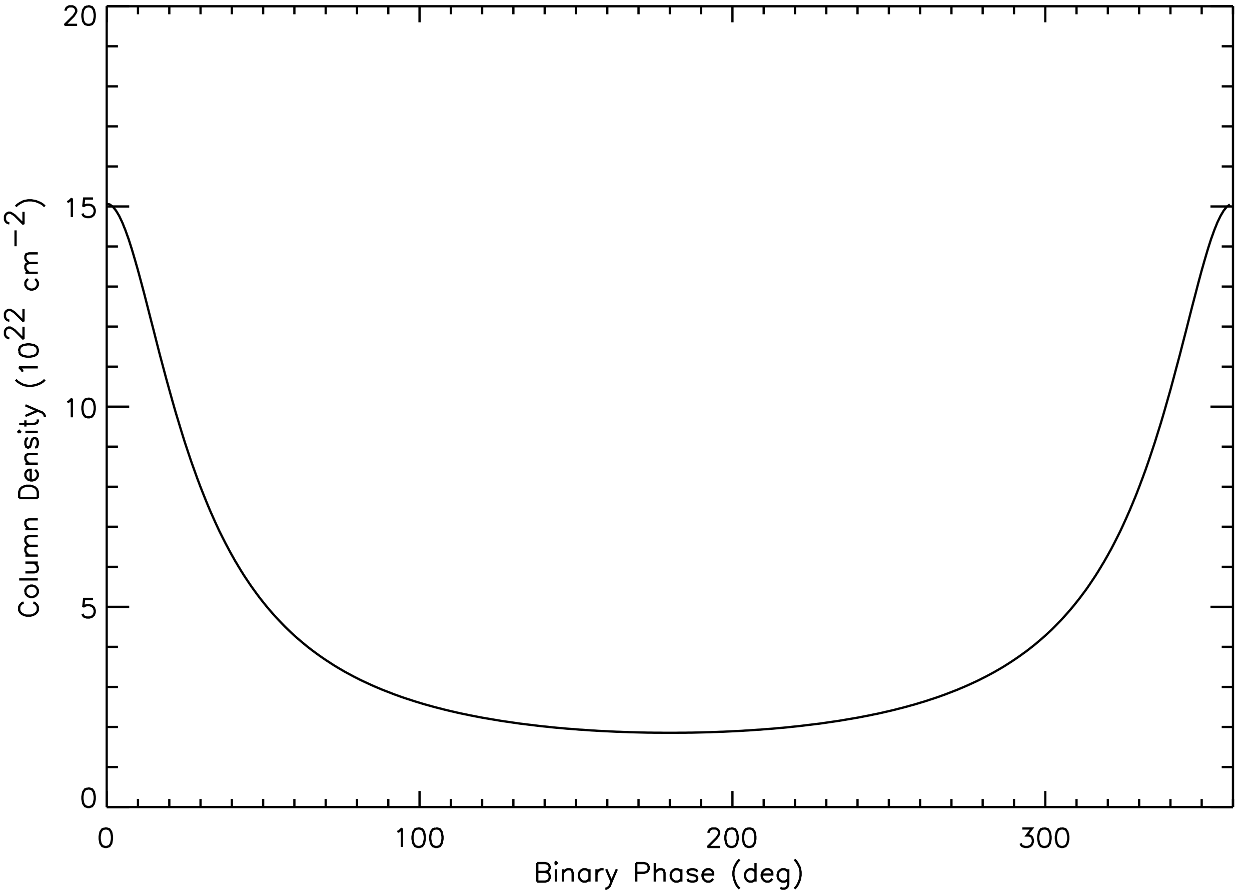

Fig. 1.— Orbital variation of observed X-ray absorption column density for wind-fed accretion from an LBV-type star. Assumes $\dot{M} = 2.65 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$, $a = 2.9$ AU, and $v_{wind} = 10^3$ km s^{-1} (see text for details). Note that both the maximum amplitude of the absorption and its strong variations are inconsistent with observations of GRS 1915+105.

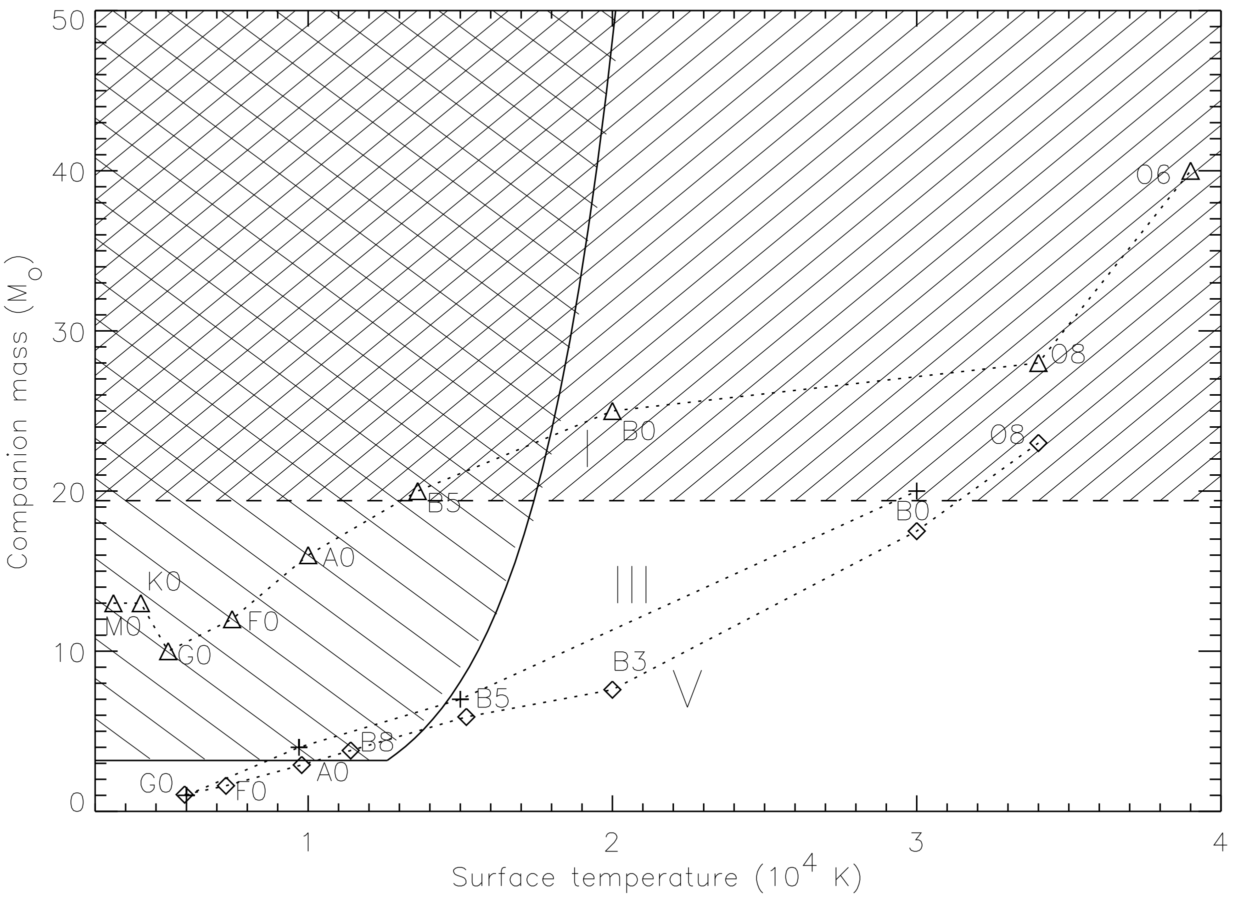

Fig. 2.— Constraints on mass and temperature for stars donating mass via Roche-lobe overflow. The hatched areas are regions which are ruled out by: (i) the limit on R_s/a (bounded by horizontal dashed line); (ii) limits on X-ray reprocessing (bounded by solid curve); (iii) the limit on $q > 0.1$ (allowing all stars with $M < 3M_\odot$). Roman numerals indicate stellar luminosity class for supergiant (I), giant (III), and main-sequence (V) stars. Assumes $M_{BH} = 30M_\odot$.