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EVIDENCE OF A BLACK HOLE IN THE X-RAY TRANSIENT GS 1354–64 (= BW CIRCINI)

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ABSTRACT

We present the first radial velocity curve of the companion star to BW Cir that demonstrates the presence of a black hole in this X-ray transient that recorded outbursts in 1987 and 1997 (and possibly 1971–1972). We identify weak absorption features corresponding to a G0–5 III donor star, strongly veiled by a residual accretion disk that contributes 61%–65% of the total light at 6300 Å. The Doppler motions of these features trace an orbit of $P = 2.54448$ days (or its 1 yr alias of $P = 2.56358$ days) and a velocity semiamplitude $K_2 = 279 \pm 5$ km s⁻¹ (or $K_2 = 292 \pm 5$ km s⁻¹). Both solutions are equally possible. The mass function implied by the shorter period solution is $f(M) = 5.75 \pm 0.30 M_\odot$, which, when combined with the rotational broadening of the tidally locked companion ($V \sin i = 71 \pm 4$ km s⁻¹), yields a compact object mass of $M_1 \sin^3 i = 7.34 \pm 0.46 M_\odot$. This is substantially above the mass of a neutron star under any standard equation of state of nuclear matter. The companion star is probably a G subgiant that has evolved off the main sequence in order to fill its Roche lobe. Remarkably, a distance of ≥ 27 kpc is inferred by the companion’s luminosity, and this is supported by the large observed systemic velocity ($\gamma = 103 \pm 4$ km s⁻¹), which requires such a distance in order to be consistent with the Galactic rotation curve.

Subject headings: accretion, accretion disks — binaries: close — stars: individual (GS 1354–64) — X-rays: stars

1. INTRODUCTION

Low-mass X-ray binaries (LMXBs) are interacting binaries in which a low-mass star transfers matter onto a neutron star or black hole (e.g., Charles & Coe 2004). Mass transfer takes place through an accretion disk where angular momentum is removed and gravitational potential energy converted into (high-energy) radiation. Accretion disks evolve toward stationary states where the mass transfer rate through the disk, \dot{M} , adjusts toward the value of \dot{M}_2 , the mass transfer rate supplied by the donor star. \dot{M}_2 is driven by the binary/donor evolution, and if $\dot{M}_2 < \dot{M}_{\text{crit}} \sim 10^{-9} M_\odot \text{ yr}^{-1}$, then mass transfer instability cycles (outbursts) are triggered (van Paradijs 1996). There are ~ 200 bright ($L_x \approx 10^{36}–10^{38}$ ergs s⁻¹) LMXBs in the Galaxy, and most of them harbor neutron stars, as implied by the detection of X-ray bursts/pulsations. On the other hand, more than 70% of transient LMXBs are known to harbor accreting black holes, as demonstrated by dynamical studies of the faint companion stars, and this is mainly possible when X-rays switch off (but see Hynes et al. 2003). We currently have dynamical evidence of 16 black hole LMXBs, with mass functions ranging from $0.22 \pm 0.02 M_\odot$ up to $9.5 \pm 3.0 M_\odot$ (see Charles & Coe 2004 and McClintock & Remillard 2004). The mass spectrum of black holes is of crucial astrophysical significance in constraining supernova models and the equation of state of nuclear matter. Clearly both more and more accurate black hole mass determinations are required before these issues can be fully addressed.

BW Cir is the optical counterpart of the X-ray transient GS 1354–64, discovered in 1987 by the *Ginga* satellite (Makino et al. 1987). It displayed X-ray properties reminiscent of black hole transients, i.e., a combination of a soft multiblackbody

component, with an inner disk temperature of ~ 0.7 keV, plus a hard power-law tail with a photon index of 2.1 (Kitamoto et al. 1990). BW Cir went into outburst again in 1997 but remained in a low/hard state throughout (Revnivtsev et al. 2000; Brocksopp et al. 2001). Interestingly, its sky position coincides with two older recorded X-ray transients, Cen X-2 and MX 1353–64, discovered in 1966 and 1971–1972, respectively (see Kitamoto et al. 1990). The former was the first X-ray transient ever discovered, with a peak soft X-ray luminosity of ~ 8 crab. If this activity were attributed to the same source, then it would make BW Cir a black hole transient with one of the shortest recurrence times ($\approx 8–10$ yr). However, the X-ray properties of these events were markedly different, and hence, if caused by the same source, it would indicate that it has displayed at least four distinct X-ray states.

BW Cir settles down in quiescence at $R = 20.5$ (Martin 1995), and as yet no indication of the orbital period exists. A possible period of ~ 46 hr and a *V*-band amplitude of 0.3–0.4 mag were reported during the 1987 outburst (Ilovaisky et al. 1987), but these have not been confirmed. On the other hand, Martin (1995) suggests a very tentative 15.6 hr periodicity with an *R*-band amplitude of ~ 0.1 mag from quiescent data, although the folded light curve does not mimic the classic ellipsoidal modulation. Here we present the first spectroscopic detection of the companion star in BW Cir and the analysis of its radial velocity curve. This provides the first dynamical probe for the presence of a black hole in this historical transient X-ray binary.

2. OBSERVATIONS AND DATA REDUCTION

We have observed BW Cir using FORS2 attached to the 8.2 m Yepun Telescope (UT4) at Observatorio Monte Paranal (ESO) on the nights of 2003 June 22–23 and 2004 May 14–15 and 25–27. A total of 55 spectra were collected with integration times varying between 1800 and 2000 s (depending on atmospheric conditions). The R1200R holographic grating was employed, and when combined with a 0.7 slit, it produced a wavelength coverage of 5745–7230 Å at 70 km s⁻¹ (FWHM) resolution, as measured from Gaussian fits to the arc lines. A He+Ne+Hg+Cd comparison lamp image was obtained with

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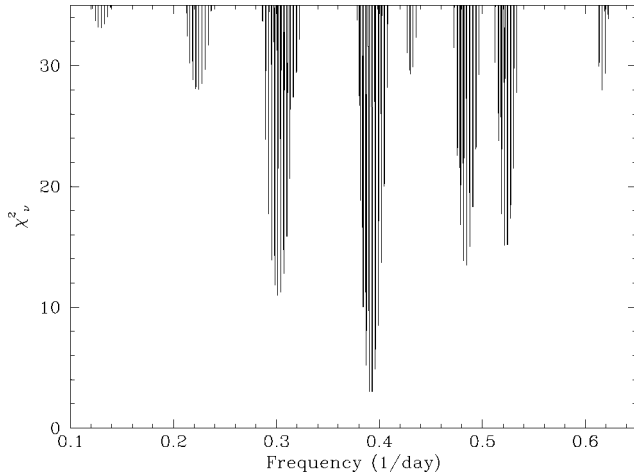


FIG. 1.—The χ^2 periodogram of the radial velocities obtained by cross-correlation with the G5 III template HD 62351. The best periods are at 0.393 day^{-1} (2.5445 days) and its 1 yr alias at 0.390 day^{-1} (2.5641 days).

the telescope in park position to provide the wavelength calibration scale. This was derived by a fourth-order polynomial fit to 37 lines, resulting in a dispersion of $0.74 \text{ \AA pixel}^{-1}$ and an rms scatter of 0.04 \AA . Instrumental flexure in our target spectra was monitored through cross-correlation between sky spectra, and it was always less than 33 km s^{-1} . These velocity drifts were removed from each individual spectrum, and the zero point of the final wavelength scale was fixed to the strong O I sky line at 6300.304 \AA . Two additional 1800 s spectra were obtained on the nights of 2000 August 23–24. Here we used the R600R grism in combination with a 0.7 slit, which resulted in a factor of 2 lower resolution.

We also observed several radial velocity and spectral type standards with exactly the same instrumental configuration on the nights of 2003 May 17 and 2004 May 27–28. These cover spectral types F5 III–K7 III. All the images were debiased and flat-fielded, and one-dimensional spectra were extracted using conventional optimal extraction techniques in order to optimize the signal-to-noise ratio of the output (Horne 1986).

3. THE RADIAL VELOCITY CURVE AND SYSTEM PARAMETERS

The 57 individual spectra were prepared for cross-correlation analysis by subtracting a low-order spline fit to the continuum and rebinning the wavelength scale into a constant step of $34 \text{ km s}^{-1} \text{ pixel}^{-1}$. Radial velocity points were extracted from our individual target spectra by cross-correlation with the radial velocity templates in the spectral range $5950\text{--}7200 \text{ \AA}$, after masking out all the emission, telluric, and interstellar (IS) absorption lines. The radial velocity points show clear night-to-night velocity changes that strongly point toward an ~ 2 day orbit. This was best seen on the nights of 2004 May 14–15, when two continuous 9 hr runs could be obtained. In order to search for the orbital period, we have performed a power spectrum analysis on the radial velocities obtained with the G5 III template, and the results are displayed in Figure 1. Frequencies longer than $0.5 \text{ cycles day}^{-1}$ (periods of <2 days) can be ruled out since they provide $\chi_r^2 > 15$. The minimum χ_r^2 ($=2.98$) is found at 0.3930 day^{-1} , corresponding to $P = 2.54446(6)$ days. However, we cannot rule out the 1 yr alias of $P = 2.56358(7)$ days with $\chi_r^2 = 3.01$. All other aliases have $\chi_r^2 > 5$ and can be rejected since they are not significant at the 99.99%.

We have performed least-squared sine-wave fits to the radial

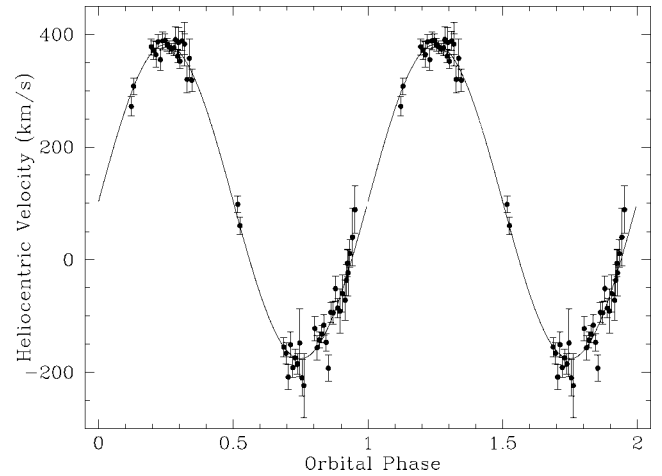


FIG. 2.—Radial velocity points of BW Cir folded on $P = 2.54448$ days and $T_0 = 2,453,140.985$ with the best-fitting sinusoid.

velocity curves obtained with all templates, and we find that spectral types in the range F5–G8 III give the best fits with χ_r^2 in the range 2–3. We decided to adopt the fitting parameters of the G5 III template since this provides the closest representation to the observed spectrum (see below); i.e., $\gamma = 103.1 \pm 4.2 \text{ km s}^{-1}$, $P = 2.54448 \pm 0.00015$ days, $T_0 = 2,453,140.985 \pm 0.013$, and $K_2 = 279.3 \pm 4.9 \text{ km s}^{-1}$ or $\gamma = 94.8 \pm 4.2 \text{ km s}^{-1}$, $P = 2.56358 \pm 0.00015$ days, $T_0 = 2,453,140.939 \pm 0.013$, and $K_2 = 291.7 \pm 5.3 \text{ km s}^{-1}$. Here T_0 corresponds to standard phase 0, i.e., the inferior conjunction of the optical star. All quoted errors are at the 68% confidence level, and we have rescaled the errors so that the minimum reduced χ^2 is 1.0. The γ -velocity has been corrected from the template's radial velocity, and we note that it is unusually large for black hole binaries and is only comparable to the long-period microquasars GRO J1655–40 and V4641 Sgr. Figure 2 presents the radial velocity points, folded on the 2.54 day period, with the best sine fit superposed. The mass function of BW Cir, for the case of the short-period solution, is $f(M) = M_1 \sin^3 i / (1 + q)^2 = PK_2^3 / 2\pi G = 5.75 \pm 0.30 M_\odot$, which defines a lower limit to the compact object's mass. This is substantially above any neutron star mass defined by all standard equations of state of condensed matter, and hence we conclude that BW Cir contains a black hole (Rhoades & Ruffini 1974).

Furthermore, our high instrumental resolution (70 km s^{-1}) enables us to measure the rotational broadening of the companion star, and we can use this information to set a more stringent limit on the black hole mass. We have broadened our G5 III template from 50 to 100 km s^{-1} in steps of 5 km s^{-1} , using a Gray profile (Gray 1992) with a linear limb-darkening law with coefficient $\epsilon = 0.62$, interpolated for $\lambda = 6300 \text{ \AA}$ and $T_{\text{eff}} \approx 5000 \text{ K}$ (see Al-Naimy 1978). The broadened versions of the template star were multiplied by fractions $f < 1$, to account for the fractional contribution to the total light, and subsequently subtracted from the grand sum spectrum of BW Cir. The latter was produced after averaging the 55 high-resolution spectra of BW Cir in the rest frame of the companion using the orbital solution above. A χ^2 test on the residuals yields $V \sin i = 71 \pm 4 \text{ km s}^{-1}$ (we have repeated the same experiment with all the templates, and $V \sin i$ always ranges between 59 and 71 km s^{-1} ; see Table 1). In the case of a tidally locked Roche lobe filling star, $V \sin i$ relates to the K_2 -velocity and the mass ratio $q = M_2/M_1$ through the expression $V \sin i \approx 0.462 K_2 q^{1/3} (1 + q)^{2/3}$ (Wade & Horne 1988), from which we obtain $q = 0.13 \pm 0.02$ and, therefore,

TABLE 1
RADIAL VELOCITY SOLUTIONS AND SPECTRAL TYPE CLASSIFICATION

| Template | Spectral Type | H α / λ 6498 | γ (km s $^{-1}$) | P (days) | T_0 (+2,453,140.0) | K_2 (km s $^{-1}$) | $V \sin i$ (km s $^{-1}$) | f | χ^2_ν |
|-----------------|---------------|-----------------------------|-----------------------------|-------------|-------------------------|--------------------------|-------------------------------|---------|--------------|
| HD 182901 | F5 III | 8.2(1) | 103(3) | 2.54447(12) | 0.987(9) | 276.4(3.4) | 66(4) | 0.47(2) | 2.50 |
| HD 83273 | G0 III | 6.0(1) | 102(3) | 2.54445(9) | 0.983(8) | 279.3(3.2) | 69(4) | 0.39(1) | 2.47 |
| HD 62351 | G5 III | 3.7(1) | 103(3) | 2.54448(9) | 0.985(8) | 279.2(2.9) | 71(4) | 0.35(1) | 2.42 |
| HR 6915 | G8 III | 2.7(4) | 104(2) | 2.54451(8) | 0.990(7) | 278.0(2.7) | 71(4) | 0.25(1) | 2.56 |
| HR 6925 | K3 III | 1.6(1) | 109(2) | 2.54451(7) | 1.000(6) | 279.2(2.0) | 59(4) | 0.15(1) | 2.58 |
| HD 184722 | K7 III | 1.3(1) | 110(2) | 2.54448(7) | 0.990(6) | 283.7(2.1) | 61(4) | 0.13(1) | 2.66 |

$M_1 \sin^3 i = 7.34 \pm 0.46 M_\odot$. Since BW Cir does not exhibit X-ray eclipses, the inclination angle must be $i \leq 77^\circ$ (for $q = 0.13$), and, consequently, the masses of the black hole and the companion star are $M_1 \geq 7.83 \pm 0.50 M_\odot$ and $M_2 \geq 1.02 \pm 0.17 M_\odot$, respectively.

For the longer period solution, the black hole case is even stronger, with $f(M) = 6.60 \pm 0.36 M_\odot$, $q = 0.12 \pm 0.02$, $M_1 \sin^3 i = 8.28 \pm 0.54 M_\odot$, $M_1 \geq 8.95 \pm 0.58 M_\odot$, and $M_2 \geq 1.07 \pm 0.19 M_\odot$. Both the long period and large mass function are reminiscent of the black hole transient V404 Cyg (Casares et al. 1992).

4. THE NATURE OF THE COMPANION STAR AND THE DISTANCE TO BW CIR

In order to refine the spectral classification, we have averaged our individual spectra in the rest frame of the companion star, using our first orbital solution, and compared it with our optimally broadened spectral type templates in the range F5–K7 III using a χ^2 minimization routine (see Marsh et al. 1994 for details). The minimum χ^2 is obtained for spectral types G0 III–G5 III, which contribute 39%–35% to the optical flux in our spectral range (see Table 1). Figure 3 presents the averaged spectrum of BW Cir in the companion’s rest frame, together with our G5 III template,⁵ broadened by $V \sin i = 71 \text{ km s}^{-1}$.

⁵ HD 62351 is a close binary with a separation of 0".4, resolvable through speckle interferometry. It is classified in the V band as G5 III or G5/6 IV (Christy & Walker 1969; Houk & Smith-Moore 1988). We confirm this classification in the R band based on the line ratio H α to λ 6498, which is very sensitive to T_{eff} (see Table 1).

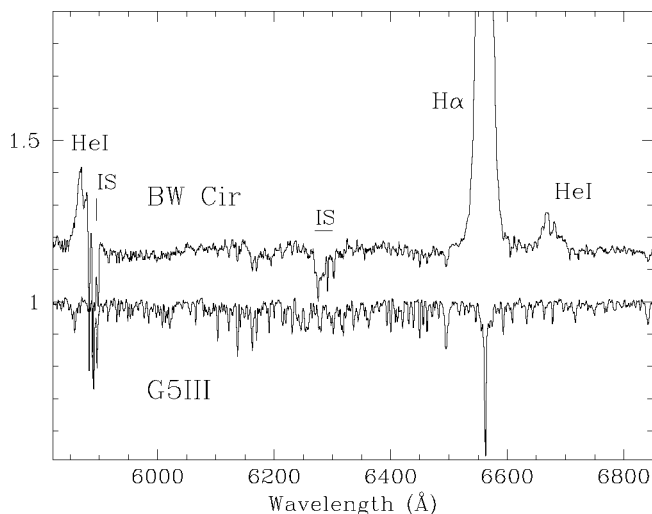


FIG. 3.—Doppler-corrected average of the 57 individual BW Cir spectra in the rest frame of the companion star and the G5 III template, broadened by 71 km s^{-1} . Note the extreme weakness of the metallic features from the companion star, as compared to the template.

A normal G0 III–G5 III star typically has $M_2 = 2.1\text{--}2.4 M_\odot$ and $R \approx 5\text{--}8 R_\odot$ (Gray 1992). However, the Roche lobe equivalent radius of a $2.1\text{--}2.4 M_\odot$ star in a 2.5 day orbit is $\approx 4.6\text{--}4.8 R_\odot$, and hence the companion is probably a lower mass, but more evolved star. Since T_{eff} is constrained by the spectral classification ($\approx 5000 \text{ K}$), and the radius of the companion by the Roche lobe geometry⁶

$$\frac{R_{L_2}}{R_\odot} \approx 0.234 \frac{P^{2/3} M_2^{1/3}}{\text{hr } M_\odot}, \quad (1)$$

we can apply the Stefan-Boltzmann relation to constrain the distance to BW Cir. Our orbital solutions yield $M_2 \geq 1.02 M_\odot$ and hence $R_2 \geq 3.6 R_\odot$. Therefore, the Stefan-Boltzmann relation gives $M_{\text{bol}} \leq 2.6$, which, when combined with the bolometric correction and $(V - R)$ color for a G5 III star (Gray 1992), gives $M_R \leq 2.11$. The dereddened magnitude of the companion star can be estimated from the observed quiescent magnitude ($R = 20.5$), corrected for reddening ($E_{B-V} \sim 1$; Kitamoto et al. 1990) and our determined 65% veiling. These yield $R \sim 19.3$. Therefore, the distance modulus relation provides a lower limit to the distance of 27 kpc that is substantially larger than the 10 kpc value proposed by Kitamoto et al. (1990). Even so, we note that this makes $L_x(1\text{--}10 \text{ keV}) = 3.5 \times 10^{37} (d/10 \text{ kpc})^2 \geq 2.6 \times 10^{38} \text{ ergs s}^{-1}$ at the peak of the 1987 outburst, still confidently below the Eddington luminosity for a $10 M_\odot$ black hole.

The distance has important implications for the observed systemic velocity. We have calculated the expected radial velocities of BW Cir, due to Galactic differential rotation, for a distance of 10 and 27 kpc, and these are -6 and 104 km s^{-1} , respectively (Nakanishi & Sofue 2003). The large distance scenario enables us to explain the observed γ -velocity without invoking any kick during the formation of the black hole. Although this scenario is the most attractive, we note the uncertainties involved in the IS extinction value, and this result requires careful consideration. Our spectrum shows several IS absorption features that can be used to obtain an independent estimate of the reddening. The strongest ones are found in the Na I doublet, for which we measure $\text{EW}(D2) = 1.37 \pm 0.04 \text{ \AA}$ and $\text{EW}(D1) = 1.66 \pm 0.04 \text{ \AA}$. The empirical calibration of Barbon et al. (1990) yields $E_{B-V} = 0.25 \times \text{EW} = 0.78$, but this should be regarded as a lower limit because Na I (D2) is somewhat diluted by the broad He I λ 5875 emission from the accretion disk. We have also measured the EW of the diffuse IS band at 6203 \AA and find $0.24 \pm 0.02 \text{ \AA}$. Using the empirical calibration between EW and reddening from Herbig (1975), we get $E_{B-V} = 0.84 \pm 0.10$. These numbers are consistent with Kitamoto et al.’s reddening of $E_{B-V} \sim 1$, which was estimated by comparing the observed outburst color of the optical

⁶ This results from combining Kepler’s third law with Paczyński’s relation (Paczynski 1971).

counterpart with typical values of luminous LMXBs given in van Paradijs (1983). This is assuming that the X-ray-irradiated disk dominated the optical emission, which is confirmed by our results here and hence gives further support to our estimated distance of ≥ 27 kpc. We note that this distance argues against BW Cir and Cen X-2 being the same object since it would make the 1966 outburst substantially super-Eddington (by more than an order of magnitude) for a 10–20 M_{\odot} black hole. However, it does make BW Cir similar to the black hole LMXB GX 339–4, for which analysis of the Na I IS absorption features at high resolution has revealed complex velocity structures, consistent with a large distance of greater than 15 kpc (Hynes et al. 2004). We also note that this implies $L_x \sim 0.1L_{\text{Edd}}$ for the 1987 hard X-ray outburst, which makes it the most luminous hard state yet seen in a black hole transient.

Additional constraints are provided by the position of the companion star in the H-R diagram, as compared with evolutionary sequences of single stars. Our spectral analysis indicates that the companion is well fitted by a G0–5 III template, and hence $T_{\text{eff}} \approx 5091\text{--}5743$ K (Gray 1992). On the other hand, combining equation (1) with the Stefan-Boltzmann relation gives $\log(L_2/L_{\odot}) \geq 4 \times \log T_{\text{eff}} - 13.92$, where we have used $M_2 \geq 1.02 M_{\odot}$. This defines a region in the H-R diagram (see Fig. 4) to compare with evolutionary tracks of 1–2 M_{\odot} stars, computed using the code BaSTI⁷ for the case of Population I stars of solar metallicity. The diagram shows that the companion star is located in the Hertzsprung gap or in the lower part of the giant branch for $M_2 \geq 1.6\text{--}1.8 M_{\odot}$. Since the luminosity of a Roche lobe filling star depends weakly on M_2 , the companion cannot be much more massive than $\approx 1.6 M_{\odot}$ (for instance, $\log L_2 = 1.06 L_{\odot}$ for $M_2 = 2.0 M_{\odot}$). If it were a 1.6 M_{\odot} star with $T_{\text{eff}} \sim 5000$ K, then $\log L_2 = 1.0 L_{\odot}$, and the distance would be ~ 33 kpc. However, we note the limitations

⁷ A. Pietriferni et al. (2004, in preparation; <http://www.te.astro.it/BASTI>).

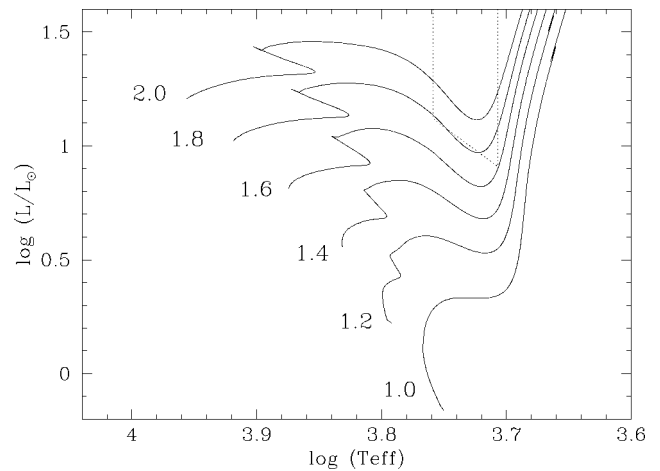


FIG. 4.—H-R diagram with evolutionary tracks of solar metallicity stars of masses 1.0–2.0 M_{\odot} . The dotted line marks the space region allowed by our spectral type classification ($T_{\text{eff}} = 5091\text{--}5743$ K) and the Stefan-Boltzmann relation for the case of a Roche lobe filling star with $M_2 \geq 1.02 M_{\odot}$ and $P = 2.544$ days.

of this crude estimate because the donor stars in X-ray binaries are not in thermal equilibrium and their H-R tracks may deviate significantly from single-star evolution.

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