A wide star-black-hole binary system from radial-velocity measurements

- LAMOST, GTC/OSIRIS, Keck/HIRES

► LB-1: (m_v = 11.5 mag - periodic radial-velocity variation)

Spectra:

► stellar absorption lines

► a broad Hα emission line

► interstellar absorption lines

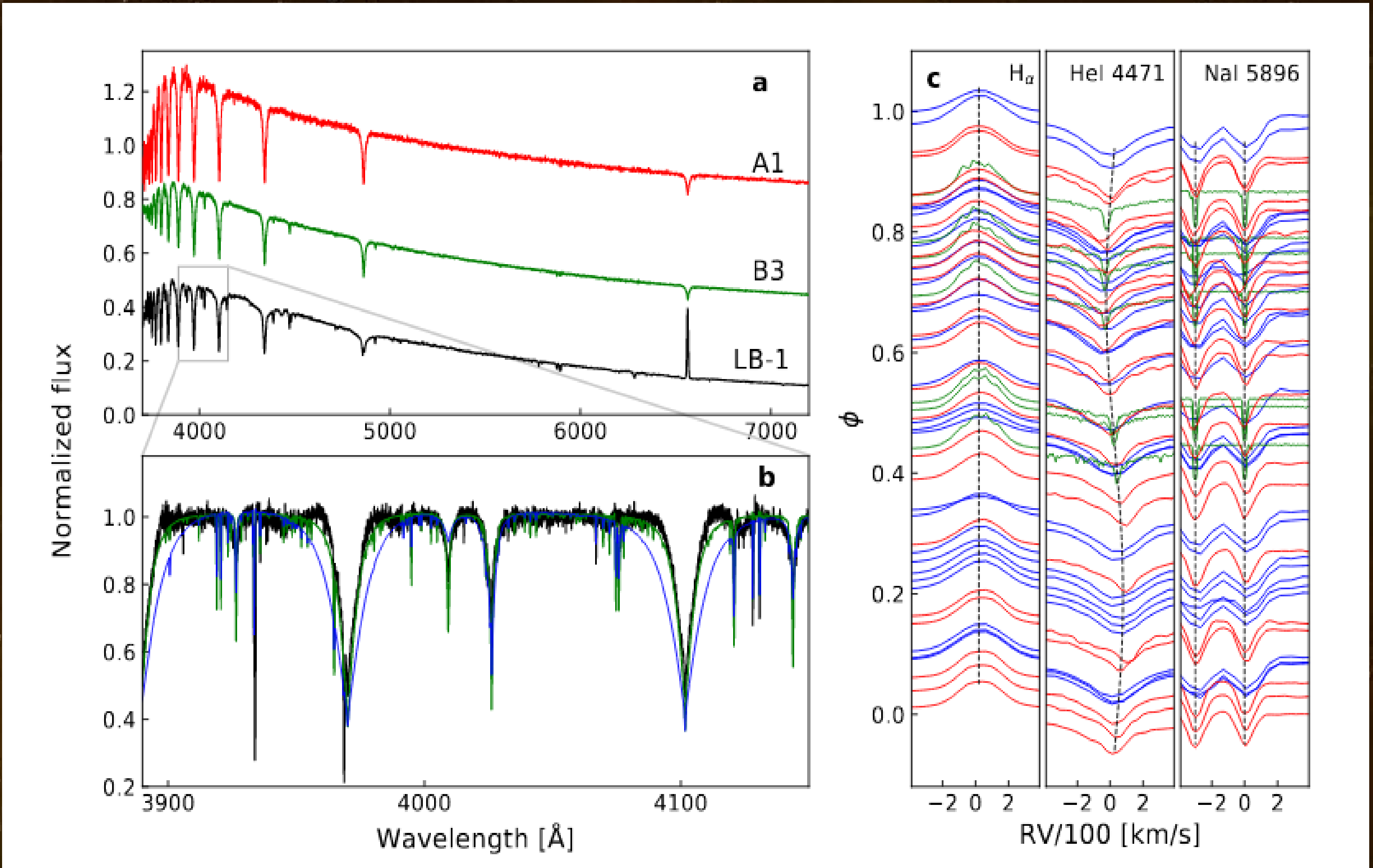


Figure 1: **Optical Spectra of LB-1.** **a,** LAMOST spectrum (thin black; $R \approx 1,800$) with stellar templates (A1: red; B3: green; offset for clarity) overplotted. **b,** Keck/HIRES spectrum of the wavelength range boxed in **a** (black; $R \approx 60,000$) with the best TLUSTY model (green; $T_{\rm eff} = 18,100\,$**K**, $\log g = 3.43$, $Z = Z_{\odot}$, $v \sin i = 10$ km/s) overplotted. The 90% confidence level (CL) errors for the model are $\Delta T_{\rm eff} = 820\,$**K** and $\Delta \log g = 0.15$. Also overplotted is a comparison model with $\log g = 4.75$ (blue), which is the highest $\log g$ of the model grid but still lower than the typical value ($\log g > 5$) for a B subdwarf. The Balmer absorption lines from this model are much wider than the observed profiles. **c,** Phased line profiles from LAMOST (blue), GTC (red) and Keck (green) observations for H_α emission line, HeI $\lambda 4471$ absorption line of the visible star, and interstellar NaI absorption lines. The dashed lines are plotted to guide the eye. The binary phase ϕ is for the period of $P = 78.9$ days.

They suggest...

- B-type star

Metallicity $= (1.2 \pm 0.2)\ Z_{\odot}$ (Si II/Mg II)

TLUSTY model:

$T_{eff} = 18{,}100 \pm 820$ K

Log$g = 3.45 \pm 0.15$

Stellar Models $\longrightarrow$

$M_B = 8.2^{(+0.9/-1.2)} M_{\odot}$

$R_B = 9 \pm 2\ R_{\odot}$

$t = 35^{(+13/-7)}$ Myr

Obs.SED vs model SED

$D = 4.23 \pm 0.24$ kpc

$E(B-V) = 0.55 \pm 0.03$ mag

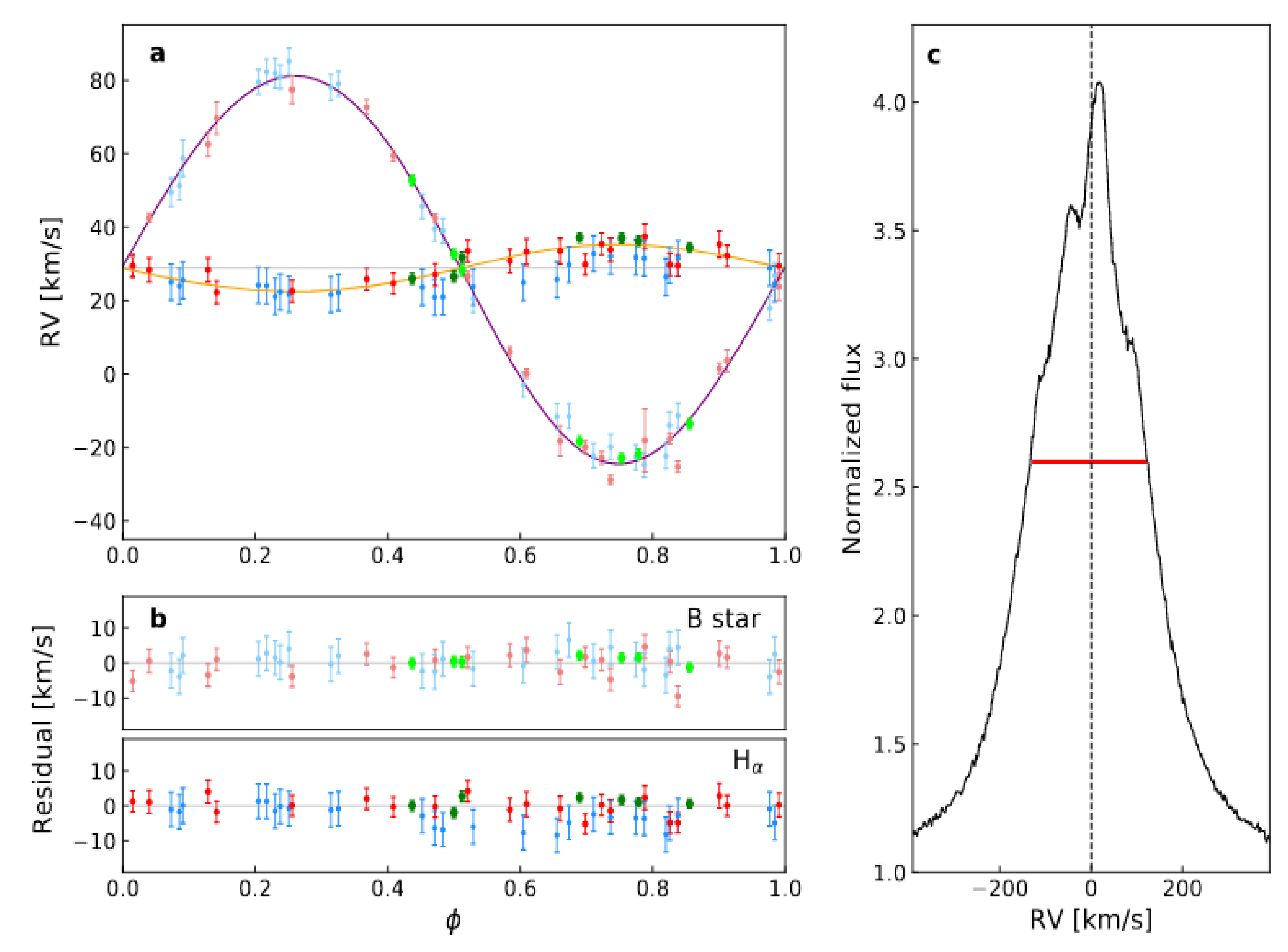


Figure 2: **Radial motions of the visible star and the dark primary.** **a,** Folded radial-velocity curves and binary orbital fits for the star and the dark primary as probed by the H_α emission line. The observed data are from LAMOST (blue), GTC (red) and Keck (green). The error bars are the quadratic sum of the wavelength calibration uncertainty and the measurement error. The best-fit binary orbit model for the star (purple) has parameters $K_{\rm B} = 52.8 \pm 0.7$ km/s, $e = 0.03 \pm 0.01$, and $V_{0\rm B} = 28.7 \pm 0.5$ km/s with a reduced χ^2 of 2.0. The best-fit model for the H_α emission line (orange) has parameters $K_\alpha = 6.4 \pm 0.8$ km/s and $V_{0\alpha} = 28.9 \pm 0.6$ km/s with a reduced χ^2 of 0.8. The errors quoted here are for 90% CL. The gray line with $V_0 = 28.8$ km/s is plotted to guide the eye. **b,** Residuals for the binary orbital fits to the star (top) and to the H_α emission line (bottom). The error bars are calculated as above. **c,** Representative H_α emission line profile from one Keck spectrum with high spectral resolution ($R \approx 60,000$). The wine-bottle shape is caused by non-coherent scattering broadening for a disk viewed nearly pole-on. The red line represents a full width at half maximum of about 240 km/s.

- $P = 78.9 \pm 0.3$ d
- From fig.2: $K_B = 52.8 \pm 0.7$km s^{-1}, $V_{OB} = 28.7 \pm 0.5$ km s^{-1},

  $e = 0.03 \pm 0.01$
- Kepler's 3rd law: $PK_B^3/2\pi G = M_{BH}^3/(M_B+M_{BH})^2\sin^3 i$

  $PK_B^3/2\pi G = (1.20 \pm 0.05)\ M_\odot$

  Given the $M_B \rightarrow$ min $M_{comp} = 6.3\ M_\odot$ for $i=90°$

  If it was a main-sequence star it could be seen $\Rightarrow$ Black Hole (BH)

<u>Hα emission:</u> gaseous Keplerian disk

1. Around B-star?
2. Around binary system?
3. Around BH ?

1. It does not trace the motion of the B star.

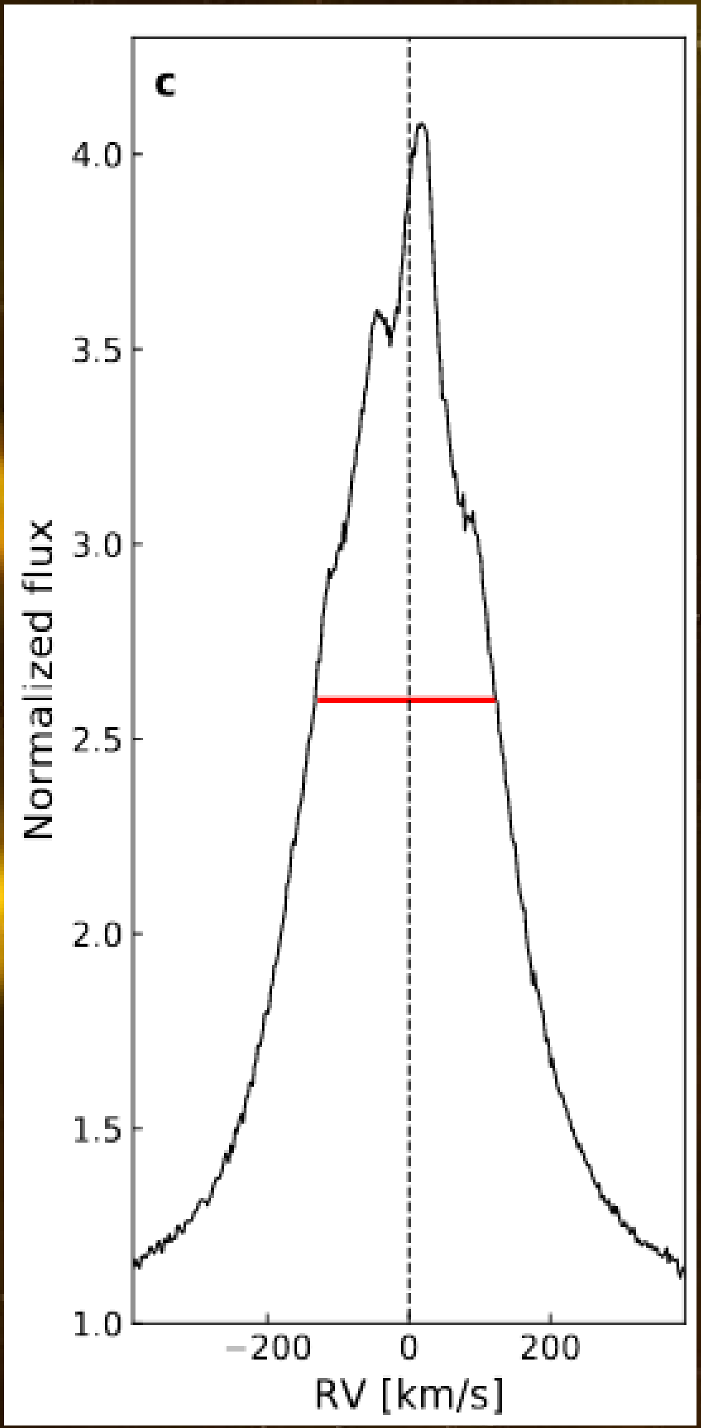
2. V << 240 km s^{-1}

3. That's the case!

From fig. 2

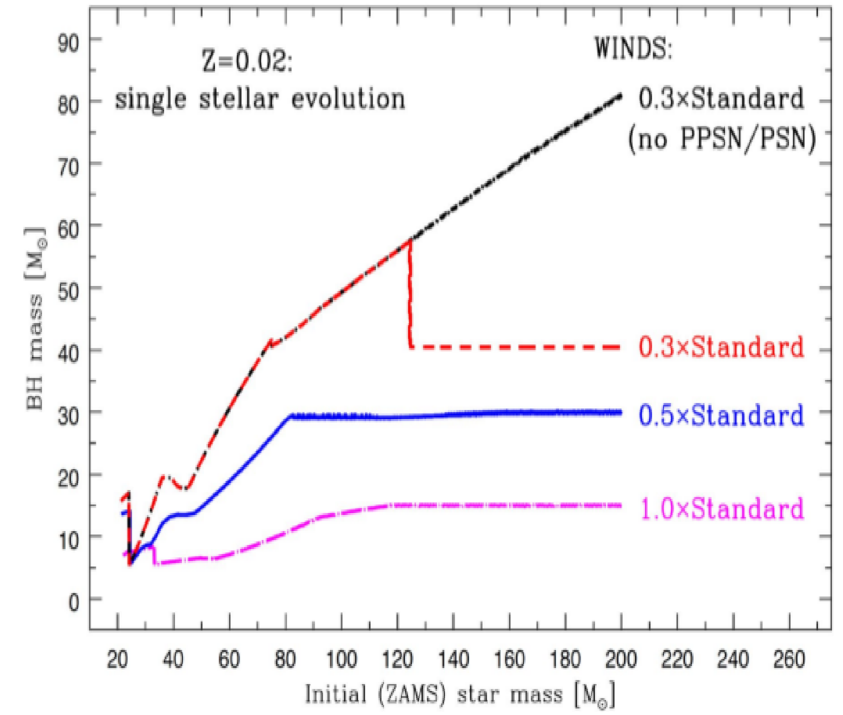
- $K\alpha = 6.4 \pm 0.8$ km s^{-1}
- $V\alpha = 28.9 \pm 0.6$ km s^{-1}
- $M_{BH}/M_B = K_B/K_\alpha \Rightarrow M_{BH} = 68^{(+11/-13)} M_☼$

$\Rightarrow i=15°-18°$



What it can be ….

- Individual stellar progenitor scenario
  A 70 M☼ BH in low metallicity environments (< 0.2 Z☼). However B-star has solar metallicity =>$M_{BH} \leq$ 25 M☼ except if reduce mass-loss rate and turn off pair-instability pulsations.



Extended Data Fig. 7 | Black-hole mass versus initial mass in the zero age main sequence (ZAMS) for single stars. For standard wind mass-loss prescriptions, only low-mass black holes are predicted: $M_{BH} < 15 M_\odot$ (pink curve). However, for reduced wind mass loss, much heavier black holes are formed: $M_{BH} = 30 M_\odot$ for winds reduced to 50% (blue curve) and $M_{BH} = 60 M_\odot$ for winds reduced to 30% (red curve) of the standard values. Note that to reach $M_{BH} = 80 M_\odot$ (black curve) it is necessary to switch off pair-instability pulsation supernovae (PPSN) or pair-instability supernovae (PSN), which severely limit black-hole masses.

- Capture

-LB-1 triple system: B-star (outermost) and BH – star$_{\geq 60 M_{\odot}}$

-LB-1 triple system: 2 BH (~ 35 M$_{\odot}$)

In those cases the LB-1's orbit wouldn't have been circularized by now.

Co-evolving binary

- fallback supernova and direct BH formation

Belczynski et al., 2019

- No X-ray detection (Chandra): $L_x \geq 2 \times 10^{31}$ erg·s^{-1})