CSIRO Publishing

Publications of the Astronomical Society of Australia

VOLUME 18, 2001

An international journal of
astronomy and astrophysics

For editorial enquiries and manuscripts, please contact:
The Editor, PASA,
ATNF, CSIRO,
PO Box 76,
Epping, NSW 1710, Australia
Telephone: +61 2 9372 4590
Fax: +61 2 9372 4310
Email: Michelle.Storey@atnf.csiro.au

For general enquiries and subscriptions, please contact:
CSIRO Publishing
PO Box 1139 (150 Oxford St)
Collingwood, Vic. 3066, Australia
Telephone: +61 3 9662 7666
Fax: +61 3 9662 7555
Email: pasa@publish.csiro.au

CSIRO
PUBLISHING

Published by CSIRO Publishing
for the Astronomical Society of Australia

www.publish.csiro.au/journals/pasa

Publ. Astron. Soc. Aust., 2001, 18, 91–97

Atmospheric Modelling of the Companion Star in GRO J1655–40

Michelle Buxton[1] and Stephane Vennes[2]

[1]Research School of Astronomy & Astrophysics, Australian National University,
Mount Stromlo Observatory, Cotter Road, Weston, ACT 2602, Australia
buxton@mso.anu.edu.au
[2]Department of Mathematics, Australian National University,
John Dedman Building, Canberra, ACT 0200, Australia
vennes@maths.anu.edu.au

Received 2000 August 24, accepted 2000 December 18

Abstract: We have measured the rotational velocity of the companion star to be $v_{\rm rot} \sin i = 80 \pm 10\,{\rm km\,s^{-1}}$ (1σ) by fitting Kurucz model spectra to our observed spectrum of the black-hole candidate GRO J1655–40. From this we have calculated $q = 0{\cdot}31 \pm 0{\cdot}08$, the mass of the compact object to be $M_1 = 7{\cdot}91 \pm 3{\cdot}79\,{\rm M}_\odot$ (1σ) and for the companion star $M_2 = 2{\cdot}76 \pm 1{\cdot}79\,{\rm M}_\odot$ (1σ), which is consistent with previous studies. We have also determined $T_{\rm eff} = 6500 \pm 50\,{\rm K}$ and $[{\rm Fe/H}] = -0{\cdot}15^{+0{\cdot}15}_{-0{\cdot}10}$.

Keywords: binaries: spectroscopic — stars: individual (GRO J1655–40) — stars: rotation

1 Introduction

The microquasar GRO J1655–40 was first discovered by the Compton Gamma Ray Observatory in 1994 (Zhang et al. 1994). It is one of only six Galactic superluminal sources observed so far, the others being 1E1740·7–2942 (Mirabel et al. 1992), GRS 1758–258 (Rodriguez, Mirabel & Marti 1992), GRS 1915+105 (Mirabel & Rodriguez 1994), XTE J1819–284 (Hjellming et al. 1999) and XTE J1748–288 (Hjellming et al. 1998). This low-mass X-ray binary (LMXB) has been extensively studied at most wavelengths (Harmon et al. 1995; Kroeger et al. 1996; Tavani et al. 1996; Hynes et al. 1998a,b). Due to its distance of only 3·2 ± 0·2 kpc (Hjellming & Rupen 1995) and relatively large quiescent brightness compared to those of other LMXBs ($V = 17{\cdot}3$ mag; Bailyn et al. 1995a), we have been able to study the companion star in this system with unprecedented coverage and accuracy. We are therefore able to derive the binary system parameters with great precision. Most other LMXBs reside within the plane of the Galaxy and are obscured by gas and dust, which block our views of their companion stars.

We have measured the rotational velocity of the companion star in GRO J1655–40 by fitting Kurucz model spectra to our spectrum of GRO J1655–40. In Section 2 we discuss how the rotational velocity of the companion star can be used to calculate the mass of the compact object, and in Section 3 consider what has been observed previously with respect to the companion star. Section 4 describes our observations and data reduction. We present radial velocities in Section 5, and our fitting code is described in Section 6. Section 7 shows our results and in Section 8 we discuss our results.

2 Measuring the Mass of the Compact Object from Companion Star Data

The mass of the compact object in GRO J1655–40 has been derived from the radial velocity curves of the secondary star (Bailyn et al. 1995b; Orosz & Bailyn 1997; Phillips, Shahbaz & Podsiadlowski 1999), from the accretion disk (Soria et al. 1998), and through modelling of optical light curves (van der Hooft et al. 1997, 1998). The results of these studies are given in Table 1. Since the theoretical mass limit of a rotating neutron star is $3{\cdot}18\,{\rm M}_\odot$ (Friedman, Ipser & Parker 1986), these results place GRO J1655–40 as one of the best black-hole candidates. We will concentrate here on another method based on the *rotational* velocity of the companion star.

The rotational velocity enables us to calculate the mass of the compact object in the following way. Let M_1 be the mass of the compact object and M_2 the mass of the companion star. The mass ratio of the binary is given by $q = M_2/M_1$. It is assumed that the companion star has filled its Roche lobe, such that (Eggleton 1983)

$$\frac{r_L}{a} = \frac{0{\cdot}49q^{2/3}}{0{\cdot}6q^{2/3} + \ln(1+q^{1/3})}, \quad 0 < q < \infty, \tag{1}$$

where r_L is the effective Roche lobe radius and a the binary separation. We also assume that the rotation of the companion star is synchronous with the orbital velocity of the binary (Paczynski 1971), leading to the equation

$$v_{\rm rot} \sin i = (K_2 + K_1)\frac{r_L}{a} = K_2(1+q)\frac{r_L}{a}, \tag{2}$$

where K_1 and K_2 are the semi-amplitudes of the radial velocity curves of the compact object and companion star, respectively, and i is the inclination of the binary. If we know K_2 and $v_{\rm rot} \sin i$, then using equations (1) and (2) we may calculate q.

The mass function of the companion star, derived from Kepler's Third Law, is given by

$$f(M_1, M_2) \equiv \frac{(M_1 \sin i)^3}{(M_2 + M_1)^2} \equiv \frac{PK_2^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}, \tag{3}$$

10.1071/AS01011 1323-3580/01/010091$05.00

Table 1. Compact object and companion star mass estimates derived for GRO J1655–40

Compact object mass ($M_{\odot}$)	Companion star mass ($M_{\odot}$)	Reference
$>3{\cdot}16 \pm 0{\cdot}15$		Bailyn et al. 1995b
$7{\cdot}02 \pm 0{\cdot}22$	$2{\cdot}34 \pm 0{\cdot}12$	Orosz & Bailyn 1997
$5{\cdot}85 \pm 0{\cdot}95$	$1{\cdot}38 \pm 0{\cdot}42$	van der Hooft et al. 1997
$>5{\cdot}1$		Soria et al. 1998
$6{\cdot}95 \pm 0{\cdot}65$	$2{\cdot}35 \pm 0{\cdot}75$	van der Hooft et al. 1998
$5{\cdot}35 \pm 1{\cdot}25$		Phillips, Shahbaz & Podsiadlowski 1999
$6{\cdot}70 \pm 1{\cdot}20$	$2{\cdot}50 \pm 0{\cdot}80$	Shahbaz et al. 1999

where P is the orbital period of the binary and can be found from the radial velocity curve of the companion. Optical light curves can also be used to measure P. Together with K_2, i and q, M_1 can then be evaluated from equation (3) and M_2 is found via q.

3 The Companion Star in GRO J1655–40

Orosz & Bailyn (1997) determined the spectral type of the companion star to be F3–F6 IV. This was achieved by comparing F–K V–III star (template) spectra to a summed, rest-frame spectrum of GRO J1655–40 from two epochs. The luminosity class is difficult to determine via this method. However, since a main-sequence F star would not be large enough to fill the Roche lobe, and the fact that F dwarf stars did not fit the GRO J1655–40 spectrum well, Orosz & Bailyn concluded that the companion star was most likely a subgiant. Although it was possible to do so, they did not calculate a rotational velocity. Using their eclipsing light curve code to model BVRI photometry of GRO J1655–40, Orosz & Bailyn derived $q = 2{\cdot}99 \pm 0{\cdot}08$ (where their $q = M_1/M_2$) and $i = 69{\cdot}50 \pm 0{\cdot}08°$. The code fits six free parameters, and errors reflect those of the internal statistics. Systematic errors were not included, as they were believed to be relatively small due to the goodness of fit to the light curves (residuals of 0·02 mag or less). From q and i, they inferred the mass of the compact object to be $7{\cdot}02 \pm 0{\cdot}22\,M_{\odot}$ and that of the companion star to be $2{\cdot}34 \pm 0{\cdot}12\,M_{\odot}$.

Shahbaz et al. (1999) measured the rotational velocity of the companion star in GRO J1655–40 using the same method as Orosz & Bailyn (1997). They found the spectral type F6 (they did not attempt to derive a luminosity class) and $v_{\rm rot} \sin i = 88{\cdot}90 \pm 6{\cdot}0\,{\rm km\,s^{-1}}$. From this, they found $q = 0{\cdot}387 \pm 0{\cdot}05$, $M_1 = 6{\cdot}70 \pm 1{\cdot}20\,M_{\odot}$ and $M_2 = 2{\cdot}50 \pm 0{\cdot}80\,M_{\odot}$.

Israelian et al. (1999) obtained spectra of an F6 III (HR 870) and an F7 IV (HR 6577) star and produced synthetic spectra based on these templates, assuming $T_{\rm eff} = 6400\,{\rm K}$, $\log g = 3{\cdot}7$, [Fe/H] $= 0{\cdot}0$ and microturbulence $\xi = 2\,{\rm km\,s^{-1}}$. Broadening both observed and synthetic spectra and comparing the result to the spectrum of GRO J1655–40, they measured $v_{\rm rot} \sin i = 93 \pm 3\,{\rm km\,s^{-1}}$. They did not derive a black-hole mass.

None of these groups have attempted to measure the effective temperature of the companion star—it has always been assumed from the spectral type. Israelian et al. (1999) measured various metallicities. In particular, they found overabundances, by factors of 6–10, in the alpha elements O, S, Mg, Si, Ti and N. However, they found [Fe/H] $= 0{\cdot}1 \pm 0{\cdot}2$, i.e. almost solar. The overabundances of the alpha elements may be due to the supernova explosion that created the compact object; it is difficult to see how such abundances can be produced in the F star. Orosz & Bailyn (1997) and Shahbaz et al. (1999) did not attempt to derive the metallicity. The rotational velocity has been measured by Shahbaz et al. (1999) using spectra of real stars that span the spectral type and luminosity class of the companion star. Israelian et al. (1999) used two synthetic spectra based on their observed stars HR 6577 and HR 870.

We have derived the rotational velocity, effective temperature and metallicity of the companion star in GRO J1655–40 by fitting Kurucz model spectra to our observed spectrum. We believe that the effective temperature should not be a fixed parameter, as an overabundance of alpha elements in the companion star may lead to a different effective temperature, which would otherwise be that assumed for normal F stars.

4 Observations and Data Reduction

Optical spectra of GRO J1655–40 were taken on the 3·9 m AAT at Siding Spring using the RGO spectrograph with a 1200R grating, giving a resolution of 1·5 Å. The slit width was 1·5″. The exposure time was 900 s for each spectrum, and a total of seven spectra were obtained over two nights (1999 April 13 and 14). Spectra of F stars in the range F2–F8 III–V and having well-known rotational velocities (Hoffleit 1982) were also obtained.

The data were reduced using standard routines in IRAF. Each spectrum was telluric-corrected, Doppler-corrected, de-reddened and normalised. All GRO J1655–40 spectra were then summed; the result is shown in Figure 1. The signal-to-noise ratio is ~55. The two main lines are Hα and a blend of Fe I, Ca I and Ba II (~6495 Å). Other lines present are mainly Fe I. If Li is present, we are unable to separate it from Fe I in our spectrum.

5 Radial Velocities

For each of our spectra, we measured the radial velocities of the Hα line only and of metal lines excluding Hα, using the FXCOR routine in IRAF. Table 2 and Figure 2

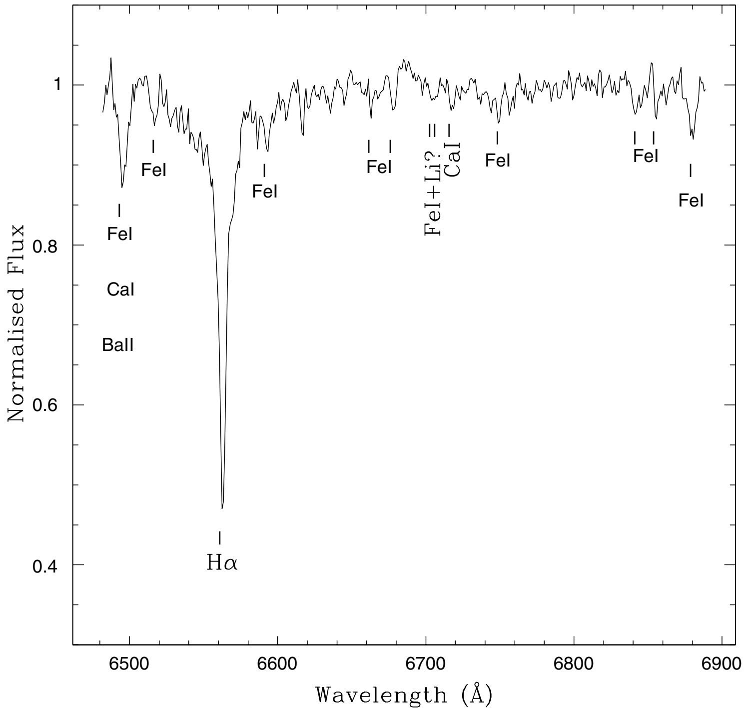

Figure 1 Summed spectrum of GRO J1655–40 with lines identified.

Table 2. Radial velocities for GRO J1655–40, obtained from Hα and metal lines (excluding Hα)

Heliocentric Julian date (−2440000)	Hα (km s^{-1})	Metal lines (km s^{-1})
11282·1163	−333·014	−319·831
11282·1605	−360·025	−347·278
11283·0649	−176·143	−175·887
11283·0868	−173·467	−129·972
11283·1157	−162·771	−132·205
11283·1377	−151·136	−124·401
11283·1593	−125·556	−106·689

show the heliocentric-corrected radial velocities in both cases. Also shown in Figure 2 is the sinusoid curve which Shahbaz et al. (1999) found by fitting their radial velocities, resulting in $K_2 = 215$ km s^{-1} and a systemic velocity $\gamma = -141{\cdot}9$ km s^{-1}.

As can be seen, Hα and the metal lines give consistent velocities within the error bars. We therefore conclude that Hα is not significantly affected by emission originating from a possible accretion disk or X-ray heating of the companion star.

In order for our points to coincide with the radial velocity curve, we have had to shift them in phase by −0·06 with respect to the van der Hooft et al. (1998) orbital ephemeris, while Shahbaz et al. (1999) shifted theirs by −0·05. This increase in phase-shift implies that the orbital period needs to be revised. As we have a very limited number of spectra, refining the orbital period from our data would be risky. It would be desirable to combine our data with those of Shahbaz et al. Unfortunately, their radial velocities (and those of other groups) have not been published in tabular form. We were unable to obtain Shahbaz et al.'s data in time to include them in this paper.

An interesting feature is found near orbital phase 0·6. Both of our (shifted) points lie well below the radial velocity curve. This has also been seen by Orosz & Bailyn (1997). In particular, the points from 1995 May 2 (when the source was in outburst) deviate significantly from the best-fit sinusoid at their orbital phase of ~0·3. Radial velocities from 1996 February 25 (quiescent period) do not deviate as much, but nevertheless have a steeper gradient than the curve, similar to the 1995 May 2 data. Phillips et al. (1999) produced a corrected radial velocity curve using a model based on an X-ray heated companion star and using only radial velocities which were obtained during outburst. Their fit to the data was an improvement on past efforts, however, there is still a hint of deviation away from the curve near orbital phase 0·6. Shahbaz et al. (1999) did not obtain any data at this phase. It is difficult to conclude from our data alone whether this feature is present in both outburst and quiescent data. Observers may wish to concentrate on this area in the future.

6 Fitting Code

Grids of model atmospheres were obtained from Robert Kurucz's web page (http://cfaku5.harvard.edu/) and spectra were produced from these using Kurucz's FORTRAN code SYNTHECD with the linelist from CD-ROM 23. Two sets of model spectra were made in which ξ was either 1·0 or 2·0 km s^{-1}. All spectra span the parameters $T_{\rm eff}$, log g and [Fe/H] as shown in Table 3. Each model spectrum was convolved to the instrument resolution and

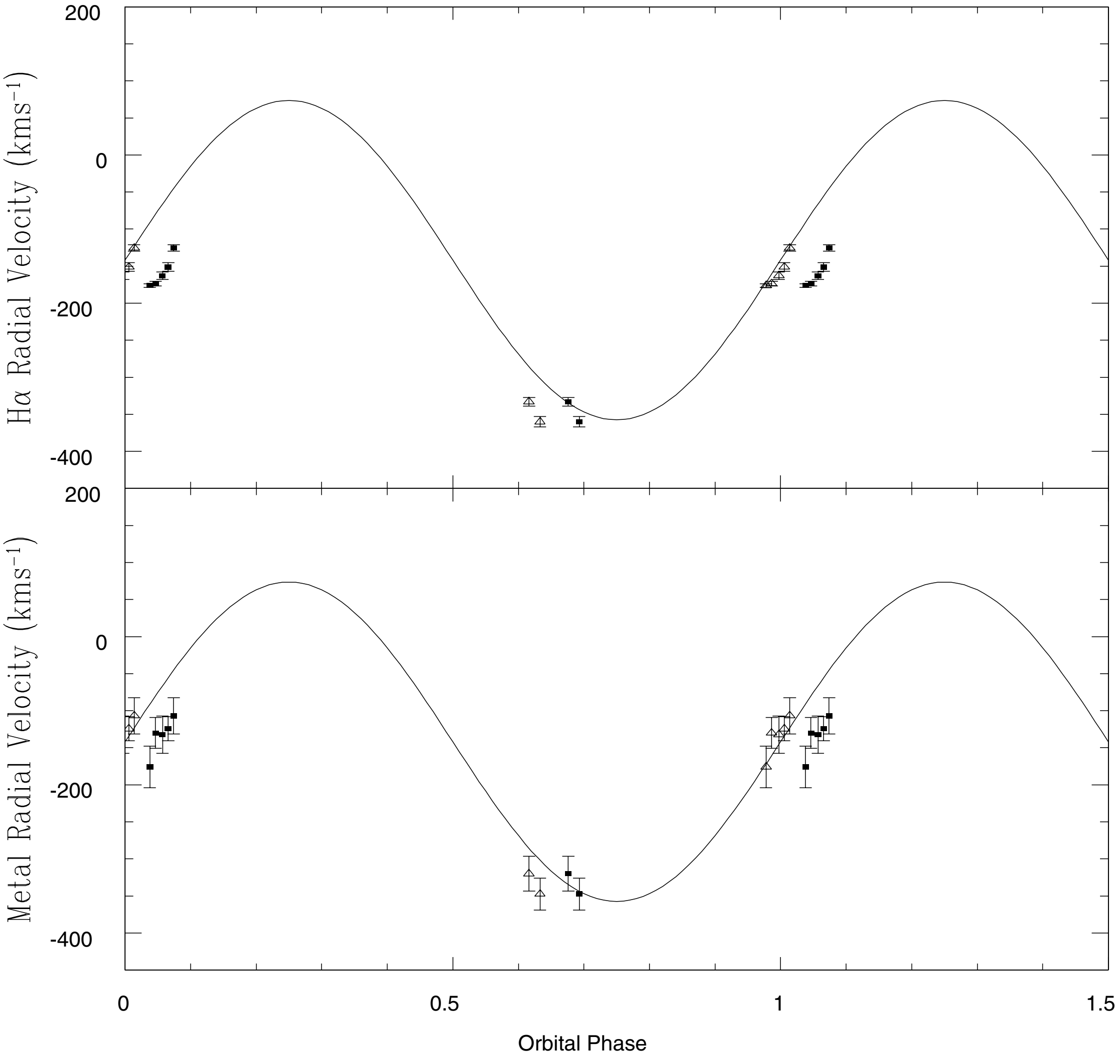

Figure 2 Heliocentric-corrected radial velocities for GRO J1655–40 spectra. The sinusoid curve has $K_2 = 215\,\mathrm{km\,s^{-1}}$ and $\gamma = -141{\cdot}9\,\mathrm{km\,s^{-1}}$ (Shahbaz et al. 1999); the phases are calculated from the van der Hooft et al. (1998) orbital ephemeris. Filled squares are radial velocities without any phase shift, while open triangles are those shifted by $-0{\cdot}06$. Upper panel: Radial velocities measured for Hα line only. Lower panel: Radial velocities measured for metal lines, excluding Hα.

Table 3. Kurucz model spectra parameters

Parameter	Range	Step
T_{eff} (K)	5500–7000	500
$\log g$	3·0–4·5	0·5
[Fe/H]	−1·0–1·0	1·0
$v_{\mathrm{rot}} \sin i$ ($\mathrm{km\,s^{-1}}$)	0–150	50

resampled in flux corresponding to the wavelengths in the GRO J1655–40 spectrum. They were then rotationally broadened to the grid $v_{\mathrm{rot}} \sin i$ values (Table 3). Our program interpolates between these models and performs a minimum-χ^2 fit over the range 6480–6600 Å, determining the best model fit to our data.

7 Results

We found during initial tests that gravity was not well constrained, as it is primarily determined by Hα. Our spectra do not cover any other Balmer lines that could be used to determine $\log g$ more accurately. The value of $\log g$ was therefore fixed at 3·7 (Israelian et al. 1999). We also found that the fits were better for the F-star spectra with $\xi = 1\,\mathrm{km\,s^{-1}}$ and for GRO J1655–40 with $\xi = 2\,\mathrm{km\,s^{-1}}$. Limb darkening for GRO J1655–40 was set at 0·5 (Allen 1963; Andersen, Clausen & Nordström 1984).

We tested our program on the solar spectrum convolved to our instrument resolution. The result is shown in Figure 3a. The fit is good and our best-fit parameters are given in Table 4 with a comparison to published values. Another test was made on our F-star template spectra. We show a typical fit to one F star (HR 5455) in Figure 3b, and note that this also is a good fit, consistent with the literature (Table 5). We are therefore confident that our program is working satisfactorily.

Figure 4 and Table 6 give the fit results for GRO J1655–40. Our fitting code gives $v_{\mathrm{rot}} \sin i = 80 \pm 10\,\mathrm{km\,s^{-1}}$ (1σ).

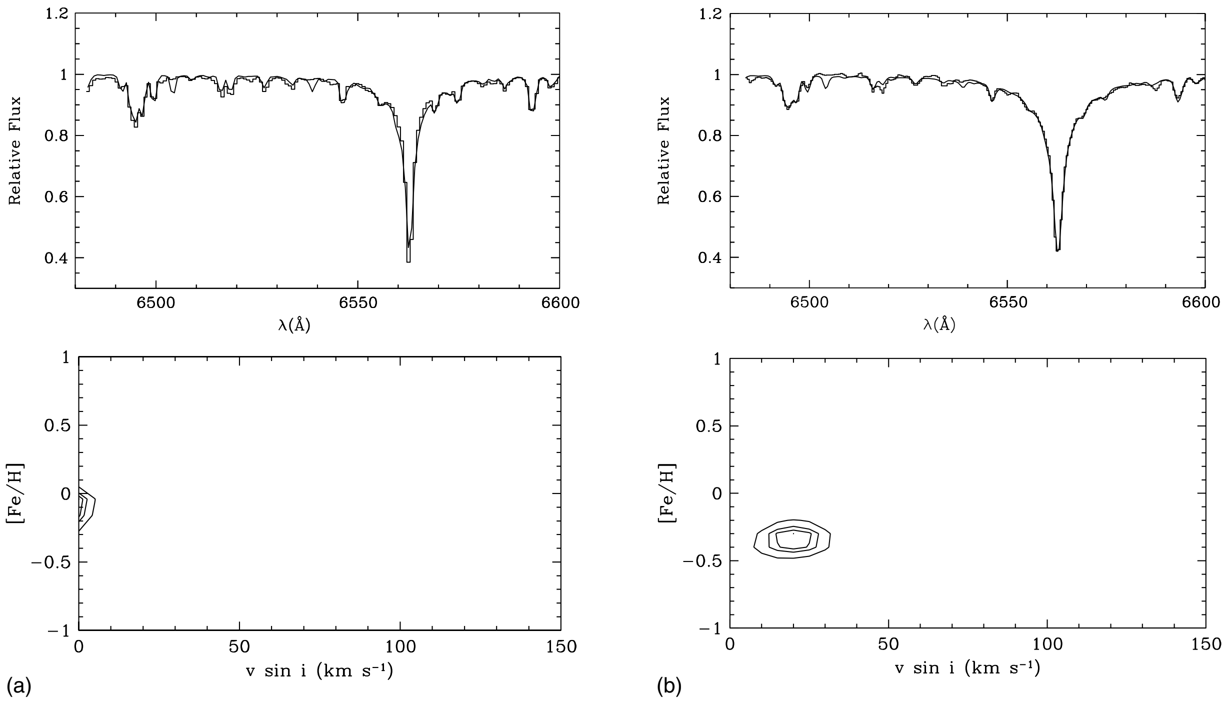

Figure 3 (a) Model fit of the solar spectrum. Top: Histogram is solar spectrum, smooth line is model fit. Bottom: 1σ, 2σ and 3σ level contours of minimum-χ^2 fit. (b) Model fit to HR 5455 (F V star) template spectrum. Top: Histogram is HR 5455 spectrum, smooth line is the model fit. Bottom: 1σ, 2σ and 3σ level contours of minimum-χ^2 fit. See also Tables 4 and 5.

Table 4. Fitting results for solar spectrum

Parameter	Best-fit value	Published values	Reference
$T_{\rm eff}$ (K)	5750 ± 25	5800 ± 15	1
[Fe/H]	$-0{\cdot}04^{+0{\cdot}01}_{-0{\cdot}13}$	0·0	definition
$v_{\rm rot} \sin i$ (km s^{-1})	0–2	2	2

(1) Allen 1963; (2) Wöhl & Schmidt 2000.

Table 5. Fitting results for HR 5455 (F5 V star) spectrum

Parameter	Best-fit values	Published values	Reference
$T_{\rm eff}$ (K)	6200^{+20}_{-10}	6146	1
		6313	2
[Fe/H]	$-0{\cdot}3^{+0{\cdot}02}_{-0{\cdot}1}$	−0·22	1
		−0·19	2
$v_{\rm rot} \sin i$ (km s^{-1})	20 ± 5	15	3

(1) Boesgaard & Tripicco 1986; (2) Balachandran 1990; (3) Hoffleit 1982.

Taking our value for $v_{\rm rot} \sin i$ and $K_2 = 215\,{\rm km\,s^{-1}}$ (Shahbaz et al. 1999), we find, using equations (1) and (2), that $q = 0{\cdot}31 \pm 0{\cdot}08$. Therefore, from equation (3) and taking $i = 67{\cdot}20 \pm 3{\cdot}50°$ (van der Hooft et al. 1998), $M_1 = 7{\cdot}91 \pm 3{\cdot}79\,{\rm M}_\odot$ (1σ). From q, we infer $M_2 = 2{\cdot}76 \pm 1{\cdot}79\,{\rm M}_\odot$ (1σ). These results agree well with those of Orosz & Bailyn (1997) and Shahbaz et al. (1999) as well as other published results (Table 1).

8 Discussion

Our radial velocities needed to be shifted in phase by −0·06 in order to coincide with the sinusoid curve derived by Shahbaz et al. (1999), who, in turn, needed to shift their radial velocities by −0·05 with respect to the orbital ephemeris of van der Hooft et al. (1998). This suggests that the orbital period needs to be refined, which we cannot do with such a limited dataset. It is possible that a deviation

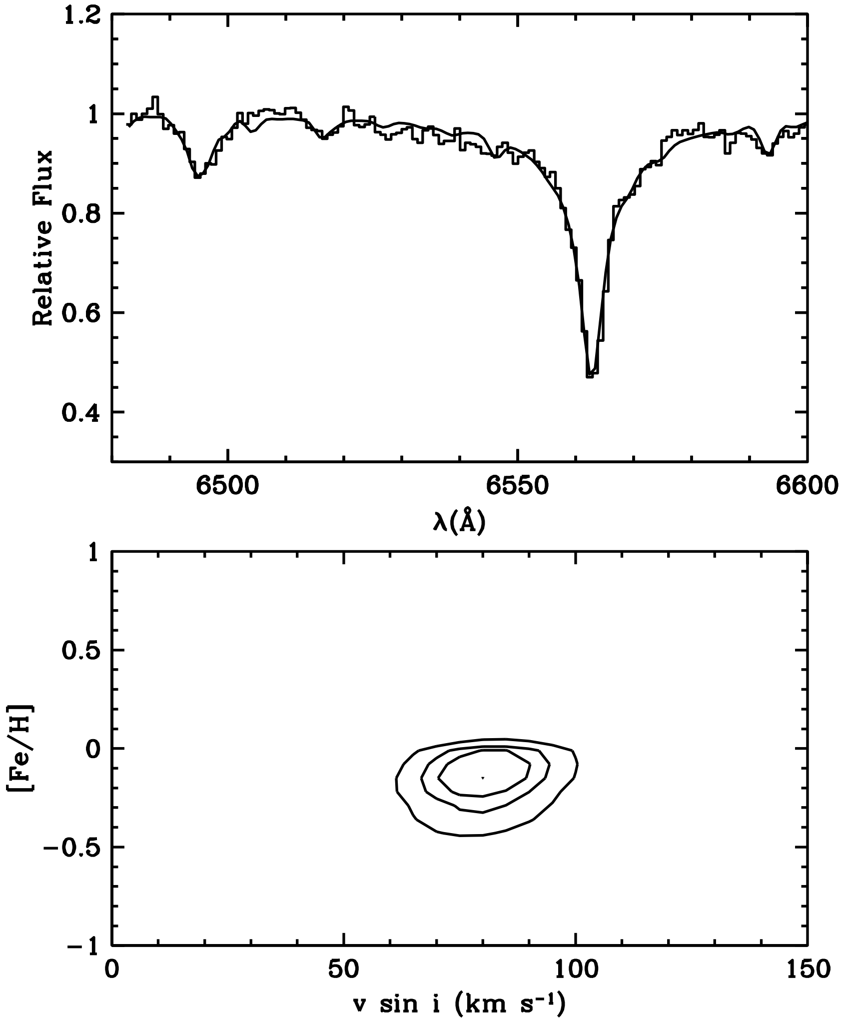

Figure 4 Model fit to summed GRO J1655–40 spectrum. Top: Histogram is GRO J1655–40 spectrum, smooth line is model fit. Bottom: 1σ, 2σ and 3σ level contours of minimum-χ^2 fit.

Table 6. Fitting results for summed GRO J1655–40 spectrum

Parameter	Best-fit values	Published values	Reference
T_{eff} (K)	6500 ± 50		
[Fe/H]	$-0{\cdot}15^{+0{\cdot}15}_{-0{\cdot}10}$	$0{\cdot}1 \pm 0{\cdot}2$	1
$v_{\mathrm{rot}} \sin i$ (km s^{-1})	80 ± 10	$88{\cdot}9 \pm 6$	2
		93 ± 3	1

(1) Israelian et al. 1999; (2) Shahbaz et al. 1999.

from the radial velocity curve exists at orbital phase 0·6. Future observations at this orbital phase would be valuable to see whether this is indeed the case in quiescence.

We have used Kurucz model spectra to measure the rotational velocity, effective temperature and metallicity of the companion star in GRO J16550–40. Our value of $v_{\mathrm{rot}} \sin i$ is consistent with those of Shahbaz et al. (1999) and Israelian et al. (1999). This rotational velocity leads to a companion star mass $M_2 = 2{\cdot}76 \pm 1{\cdot}79\,\mathrm{M}_\odot$ (1σ) and compact object mass $M_1 = 7{\cdot}91 \pm 3{\cdot}79\,\mathrm{M}_\odot$ (1σ), also consistent with the literature and strengthening the evidence that this is a black hole.

Acknowledgments

We thank Dayal Wickramasinghe and Lilia Ferrario for their helpful discussions. Stephane Vennes is a QEII Fellow of the ARC. Michelle Buxton thanks the ASA Council for funding assistance to present this paper overseas.

References

Allen, C. W. 1963, in Astrophysical Quantities, 2nd edn (London: The Athlone Press, University of London), p. 162
Andersen, J., Clausen, J. V., & Nordström, B. 1984, A&A, 137, 281

Bailyn, C. D., et al. 1995a, Nature, 374, 701
Bailyn, C. D., Orosz, J. A., McClintock, J. E., & Remillard, R. A. 1995b, Nature, 378, 157
Balachandran, S. 1990, ApJ, 354, 310
Boesgaard, A. M., & Tripicco, M. J. 1986, ApJ, 303, 724
Eggleton, P. P. 1983, ApJ, 268, 368
Friedman, J. L., Ipser, J. R., & Parker, L. 1986, ApJ, 304, 115
Harmon, B. A., et al. 1995, Nature, 374, 703
Hjellming, R. M., & Rupen, M. P. 1995, Nature, 375, 464
Hjellming, R. M., et al. 1998, AAS 193, #103. 08
Hjellming, R. M., et al. 1999, AAS 195, #134. 03
Hoffleit, D. 1982, in The Bright Star Catalogue, 4th revised edn (New Haven: Yale University Observatory)
Hynes, R. I., O'Brien, K., Horne, K., Chen, W., & Haswell, C. A. 1998a, MNRAS, 299, L37
Hynes, R. I., et al. 1998b, MNRAS, 300, 64
Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L. 1999, Nature, 401, 142
Kroeger, R. A., et al. 1996, A&AS, 120, 117
Mirabel, I. F., Rodriguez, L. F., Cordier, B., Paul, J., & Lebrun, F. 1992, Nature, 358, 215
Mirabel, I. F., & Rodriguez, L. F. 1994, Nature, 371, 46
Orosz, J. A., & Bailyn, C. D. 1997, ApJ, 477, 876
Paczynski, B. 1971, ARA&A, 9, 183
Phillips, S. N., Shahbaz, T., & Podsiadlowski, Ph. 1999, MNRAS, 304, 839
Rodriguez, L. F., Mirabel, I. F., & Marti, J. 1992, ApJ, 401, L15
Shahbaz, T., van der Hooft, F., Casares, J., Charles, P. A., & van Paradijs, J. 1999, MNRAS, 306, 89
Soria, R., Wickramasinghe, D. T., Hunstead, R. W., & Wu, K. 1998, ApJ, 495, L95
Tavani, M., et al. 1996, ApJ, 473, L103
van der Hooft, F., et al. 1997, MNRAS, 286, L43
van der Hooft, F. F., Heemskerk, M. H. M., Alberts, F., & van Paradijs, J. 1998, A&A, 329, 538
Wöhl, H., & Schmidt, W. 2000, A&A, 357, 763
Zhang, S. N., et al. 1994, IAUC Circ., 6046