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MEASURING THE MOTION OF THE BLACK HOLE IN GRO J1655−40

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ABSTRACT

We report optical spectroscopic observations of the low-mass X-ray binary GRO J1655−40 during outbursts in 1994 August–September and in 1996 June. The spectra show emission and absorption lines from the accretion disk surrounding the X-ray source, which have enabled us to measure the motion of the black hole candidate in this system. It is the first time among black hole candidates that an emission-line radial velocity curve is seen in phase with the expected motion of the primary. The projected radial velocity semiamplitude determined for the primary ($K_X = 76.2 \pm 7.5$ km s^{-1}), combined with estimates of the projected radial velocity semiamplitude of the companion star from previous observations ($K_C = 228.2 \pm 3.0$ km s^{-2}), yields a 95% confidence limit, derived purely from kinematics, of $M_X > 5.1\ M_\odot$ for the mass of the compact object in GRO J1655−40, confirming its black hole nature.

Subject headings: accretion, accretion disks — binaries: spectroscopic — black hole physics — stars: individual (GRO J1655−40)

1. INTRODUCTION

The soft X-ray transient low-mass X-ray binaries have proved to be an ideal hunting ground for stellar-mass black hole candidates (Tanaka & Lewin 1995). Among the X-ray binaries commonly discussed as being most likely to harbor black holes, all but three (Cyg X-1, LMC X-1, and LMC X-3) belong to this class. Of these, the recently discovered GRO J1655−40 is particularly interesting as well for being a source of superluminal radio jets (Zhang et al. 1994; Harmon et al. 1995). Given its optical brightness and some evidence of eclipse-like features, it appears to be one of the few systems likely to yield a reliable estimate for the mass of the collapsed star.

In all but the faintest systems, it is possible to determine the projected radial velocity of the companion star v_C, which, for a circular Keplerian orbit, is given by

$$v_C(t) = K_C \cos[2\pi\phi(t)] + \gamma,$$

where γ is the systemic velocity and $\phi(t)$ is the orbital phase. The measurement of the orbital period P and the projected radial velocity semiamplitude K_C leads to an estimate of the optical mass function:

$$f_C \equiv \frac{(M_X \sin i)^3}{(M_C + M_X)^2} \equiv \frac{M_X \sin^3(i)}{(1+q)^2} = \frac{PK_C^3}{2\pi G}$$

(van Paradijs & McClintock 1995; Shapiro & Teukolsky 1983), where $q \equiv M_C/M_X$, M_X and M_C are the masses of the compact object and of the companion star, respectively, and i is the inclination angle of the orbital plane.

An estimate of M_C can usually be obtained from the spectral type and the luminosity of the companion. Modeling the ellipsoidal intensity variations of the companion during a low state is another way to determine q and i. These methods have been applied with considerable success to GRO J1655−40 (Orosz & Bailyn 1997), yielding $K_C = 228.2 \pm 3.0$ km s^{-1}, $\gamma = -142.4 \pm 1.6$ km s^{-1}, $f_C = 3.24 \pm 0.09\ M_\odot$, $M_C = 2.34 \pm 0.12\ M_\odot$, $i = 69\overset{\circ}{.}5 \pm 0\overset{\circ}{.}08$, and $M_X = 7.02 \pm 0.22\ M_\odot$.

Nevertheless, given the uncertainties in estimating the mass of the companion star from its spectral type, and in modeling the ellipsoidal variations in the presence of an accretion disk, an independent mass estimate is desirable. This can be achieved by determining the radial velocity curve of the X-ray source. In the case of neutron star (NS) X-ray binaries, one can often measure the Doppler shift of coherent X-ray pulses from the central object, whereas in black hole (BH) binaries, one has to resort to optical studies of the accretion disk (Orosz et al. 1994). Measuring the radial velocity curve of the primary would allow us to determine the X-ray mass function:

$$f_X \equiv \frac{(M_C \sin i)^3}{(M_C + M_X)^2} \equiv \frac{M_C \sin^3(i)}{(1+1/q)^2} = \frac{PK_X^3}{2\pi G}.$$

All the physical parameters would then be determined as a function of i. For example, $q \equiv M_C/M_X = K_X/K_C = (f_X/f_C)^{1/3}$, and $M_X = f_C(1+q)^2(\sin i)^{-3}$.

In the following sections, we discuss the results of spectroscopic observations carried out during outbursts in 1994 and 1996. In particular, we focus on the radial velocity variations of the He II λ4686 emission line, from which we infer the velocity curve of the primary. We also examine the fluorescence lines N III λλ4641, 4642, which appear to come from a hot spot near the outer edge of the accretion disk.

2. OBSERVATIONS AND RESULTS

GRO J1655−40 was observed briefly, as a target of opportunity, on each night from 1994 August 30 to September 4 with the Royal Greenwich Observatory spectrograph and Tektronix 1 K × 1 K thinned CCD on the 3.9 m Anglo-Australian Telescope. Spectra of two wave bands were obtained: the 6278–6825 Å band (centered on Hα) and the 4432–5051 Å band (covering N III, He II, and Hβ); 1200 g mm^{-1} gratings were used for both bands, oriented with the blaze direction toward the 25 cm camera, and the resolution was 1.3 Å FWHM.

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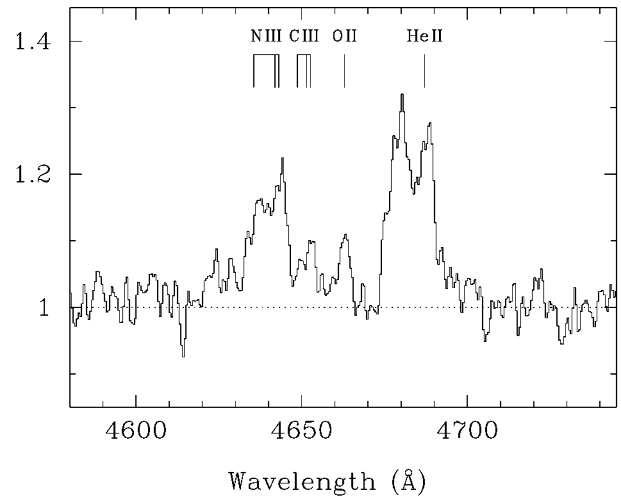

FIG. 1.—Portion of the blue spectrum of GRO J1655−40 obtained by co-adding the spectra taken on 1996 June 8 (orbital phases $0.07 < \phi < 0.17$) with the ANU 2.3 m telescope at Siding Spring Observatory. Wavelengths are vacuum heliocentric, and the intensity is normalized to the continuum, shown as a dotted line. Lines clearly identifiable are He II λ4686; N III λλ4634, 4641, 4642; C III λλ4647, 4650, 4651; O II λ4662.

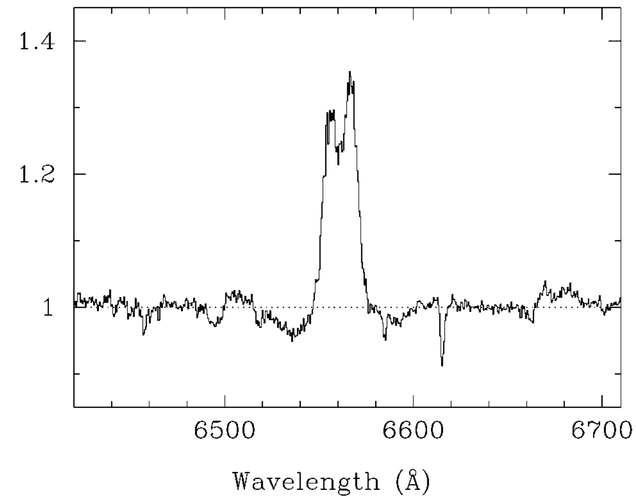

FIG. 2.—Portion of the red spectrum of GRO J1655−40 obtained by co-adding all the spectra taken in 1996 June with the ANU 2.3 m telescope at Siding Spring Observatory; as in Fig. 1, wavelengths are vacuum heliocentric, and the intensity is normalized to the continuum. The double-peaked Hα λ6562 emission line is prominent; the peak-to-peak separation is ~500 km s^{-1}. A much weaker, double-peaked He I λ6678 line can also be identified, and the blend Fe I λλ6495, 6496, 6499, 6502 is visible in absorption. The absorption line at 6613 Å is interstellar.

More extensive observations were carried out on 1996 June 8–12 using the Double Beam Spectrograph on the 2.3 m Australian National University (ANU) telescope at Siding Spring Observatory, with 1200 g mm^{-1} gratings for both the blue (4150–4990 Å) and the red (6300–7200 Å) spectral regions (resolution 1.2 Å FWHM); the detectors used were SITe 1752 × 532 CCDs in both arms of the spectrograph. Conditions were not photometric in 1996 June, and we normalized the spectra to the continuum level, using the CONTINUUM task in IRAF. Both in 1994 August–September and in 1996 June, the optical spectrum was dominated by a bright accretion disk. In both sets of data, we observed strong, double-peaked Hα and He II λ4686 emission lines and much weaker emission from Hβ, Hγ, and He I λ6678. Strong emission was consistently seen from the Bowen fluorescence lines of N III λλ4634, 4641, 4642, with weak emission lines of C III, N II, and O II identified at some orbital phases. The H I Balmer lines also show a broad absorption trough, much broader than the emission line (Hunstead, Wu, & Campbell-Wilson 1997). Some narrow absorption lines from the spectrum of the companion star are also detectable, although they tend to be swamped by the bright continuum emission from the disk. A portion of the He II region obtained by co-adding the data taken on 1996 June 8 is shown in Figure 1; a portion of the Hα spectrum obtained by co-adding all 1996 June data is shown in Figure 2.

3. RADIAL VELOCITY CURVE OF THE PRIMARY

Radial velocity variations of disk emission lines were measured by Haswell & Shafter (1990) for the X-ray binary A0620−00 and by Orosz et al. (1994) for A0620−00 and GRS 1124−68, in each case to determine the mass of the primary. One method for determining the central position of the line is to convolve the data with two identical Gaussian bandpasses. When the counts in each bandpass are equal, the midpoint between the two Gaussians is the wavelength of the spectral line. This method assumes that the observed line profile is symmetric. Another way of finding the line center is to fit the theoretical profile expected for a line emitted from the surface of a geometrically thin disk (Smak 1981; Horne & Marsh 1986), either to both wings and both peaks or only to the red wing and peak. By fitting sine curves to the Hα radial velocity curves for A0620−00 and GRS 1124−68, Orosz et al. (1994) found that the semiamplitudes are consistent with the mass ratios previously estimated for the two systems, but that there is in both cases a phase shift of ~40° from the expected radial velocity of the primary.

In our study of GRO J1655−40, we focus on the velocity variations of He II λ4686, for which we have the best phase coverage. The velocity variations were determined from the midpoint of the steep line wings at $\frac{1}{4}$ of the maximum intensity above the continuum, not by fitting to the peaks. The emission in the peaks comes from the outer rings of the disk, where emission from a hot spot and tidal effects causing deviations from Keplerian rotation can be significant; the wings are emitted at smaller radii and are probably a more reliable indicator of the line position. Errors were estimated by measuring the midpoint near the continuum level and at half-maximum. These three values do not differ by more than 0.5 Å (32 km s^{-1}) in any spectrum.

The Hα emission line has a higher signal-to-noise ratio than He II λ4686, but it cannot be used for an estimate of the orbital velocity of the disk, because the underlying broad, often asymmetric absorption does not allow an accurate determination of a midpoint position from the line wings. Furthermore, unlike He II λ4686, the Hα emission-line profile is strongly asymmetric: the surface emissivity of the disk appears to be a function of the azimuthal coordinate, and the absorption line from the companion star might also be present. For these reasons, the velocity curve of the Hα line does not reflect the orbital motion of the disk. We will discuss the Hα line profile in a paper currently in preparation.

Figure 3 shows the best sinusoidal fit to the measured heliocentric radial velocity in the 1996 data set (*filled circles*). We obtain

$$v_X(t) = 76.2 \cos\{2\pi[\phi(t) + 0.524]\} - 182.5 \text{ km s}^{-1}.$$

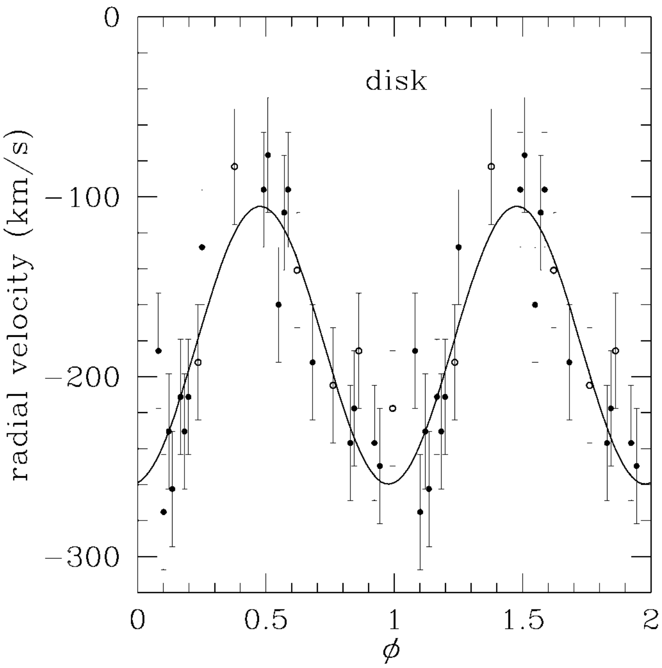

FIG. 3.—Radial velocity curve for the He II λ4686 emission line from the 1996 June (*filled circles*) and 1994 August–September data (*open circles*). Following Orosz & Bailyn (1997), we have defined $\phi = 0$ at the time of maximum redshift of the companion star according to their ephemeris. The best fit for the radial velocity curve of the disk lines (calculated only from the 1996 data) is in antiphase with respect to the star and has a semiamplitude $K_X = 76.2 \pm 7.5$ km s^{-1}.

The six positions measured in 1994 for the same line have also been plotted (*open circles*) but were not included in the calculation of the best fit, because the line profiles and equivalent widths appear very different from the 1996 spectra, and much more variable from phase to phase, as we shall discuss in more detail elsewhere. The radio and X-ray behavior in 1996 was also very different from 1994. The orbital period has been assumed to be $P = 2.62157$ days, and the phase $\phi = 0$ corresponds to the time of maximum redshift of the companion star, as determined by Orosz & Bailyn (1997) when the system was in quiescence. According to their ephemeris, the time of inferior conjunction of the secondary star is HJD 2,449,838.42(09) + 2.621(57) × N. The phase shift of $189° \pm 20°$ between the two radial velocity curves is consistent with their being in antiphase and strongly suggests that orbital motion of the disk is responsible for the effect, rather than, for example, anisotropic emission. A different ephemeris has recently been proposed by van der Hooft et al. (1998), who determine the time of inferior conjunction of the secondary star at HJD 2,449,838.4198(52) + 2.62168(14) × N; this would imply a phase shift between the radial velocity curves of the disk and the companion star of $191° \pm 20°$, fully consistent with our interpretation. If perfect antiphase is demanded in fitting the velocity curve, we obtain

$$v_X(t) = 72.1 \cos\{2\pi[\phi(t) + 0.500]\} - 181.8 \text{ km s}^{-1},$$

consistent with the previous result.

We also note that (*a*) the systemic velocity inferred from the He II radial velocity curve (-182.5 ± 5.5 km s^{-1}) is significantly larger (in absolute value) than that determined by Orosz & Bailyn (1997) from the orbital motion of the companion star (-142.4 ± 1.6 km s^{-1}); in other words, the disk emission lines appear systematically blueshifted by 40 km s^{-1}; and (*b*) the separation between the two peaks in the He II emission line is always $\lesssim$650 km s^{-1} (Fig. 1). The corresponding separation in the Hα emission line is always $\lesssim$550 km s^{-1} in the 1996 June spectra (Fig. 2) and always $\lesssim$350 km s^{-1} in the 1994 August–September spectra. It is generally assumed that in a binary system with a mass ratio $q > 0.25$, the accretion disk around the primary cannot grow any larger than the tidal truncation radius r_d (Paczyński 1977; Whitehurst 1988; Osaki, Hirose, & Ichikawa 1993), approximately given by $r_d = 0.60a/(1 + q)$ for $0.03 < q < 1$ (Warner 1995), where a is the separation between the centers of mass of the binary components. Using the orbital parameters derived in this section and in Orosz & Bailyn (1997), we derive $a \sin i = (11.0 \pm 0.3) \times 10^{11}$ cm, and $r_d \sin i = (4.9 \pm 0.2) \times 10^{11}$ cm, corresponding to a minimum value of the projected radial velocity of the outer rim of the disk $v_{\rm rim} = 391 \pm 13$ km s^{-1}. Therefore, the peak-to-peak separation in the emission lines is always less than twice the projected radial velocity of the rim.

Both phenomena are very common, not only among BH candidates but also in NS binaries and in cataclysmic variables, and may be interpreted as evidence that He II λ4686 is emitted in a wind region just above the disk surface (Murray & Chiang 1997). A similar situation may apply to the much more massive BH accretion disks in QSOs, where different emission lines are found to be systematically blueshifted with respect to the systemic redshift. The magnitude of the blueshift is roughly in order of increasing ionization, with the most extreme shift being for He II (Tytler & Fan 1992).

We must also consider the possibility of tidal deformation of the accretion disk by the companion star. It is well known, both theoretically (Paczyński 1977) and observationally (Marsh, Horne, & Shipman 1987), that if the outer rings of the disk are tidally deformed, the observed amplitude of the velocity variations of its lines is slightly larger than the real amplitude of motion of the primary. Since we are measuring the position of the wings (emitted from inner regions of the disk, $r \lesssim 0.5r_{\rm rim}$), we expect this tidal effect to be small, i.e., the true velocity of the primary may have been overestimated by $\lesssim$5%.

Neglecting tidal effects, we conclude that $K_X = 76.2 \pm 7.5$ km s^{-1}, which implies a mass ratio of $q = 0.334 \pm 0.033$. The X-ray mass function is then $f_X = 0.121 \pm 0.036\ M_\odot$, giving

$$M_X = \frac{5.77 \pm 0.33}{(\sin i)^3} M_\odot.$$

Even without any assumptions on the inclination angle, this result shows that $M_X > 5.1\ M_\odot$ (95% confidence limit), well above the Chandrasekhar limit. Our result is fully consistent with the mass ratio derived by Orosz & Bailyn (1997) and van der Hooft et al. (1998).

4. DETECTION OF THE HOT SPOT?

In our 1996 June spectra, the Bowen fluorescence emission lines (see McClintock & Canizares 1975 and Schachter, Filippenko, & Kahn 1989 for a discussion on their origin and significance) N III λ4634 and the blend N III λλ4641, 4642 are narrow and single peaked; their profiles suggest that the emission region is localized. We measured their positions by fitting Gaussian profiles. The observed radial velocities for N III λλ4641, 4642 are shown in Figure 4: the dashed line is the projected radial velocity of the companion star determined by Orosz & Bailyn (1997). It is possible that the Bowen lines are

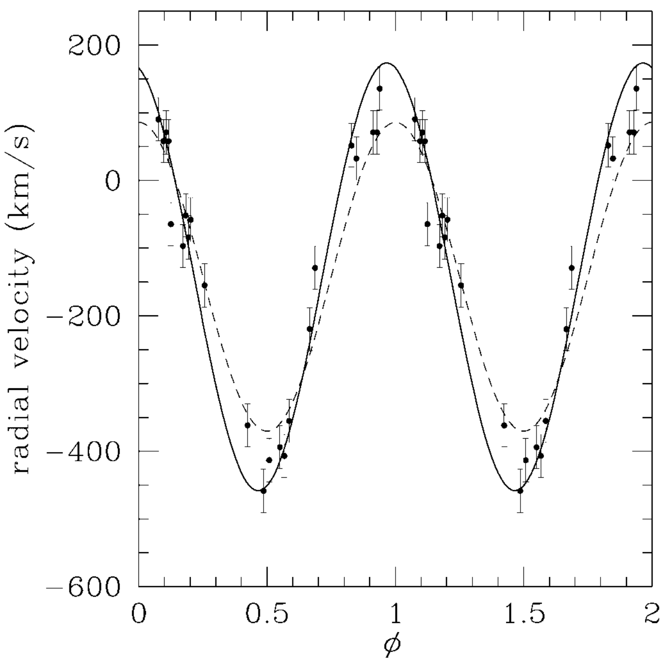

FIG. 4.—Radial velocities for the narrow Bowen fluorescence lines N III λλ4641, 4642 plotted as a function of orbital phase. The dashed line is the velocity curve of the companion star as determined by Orosz & Bailyn. The solid line is the theoretical projected radial velocity of a hot spot on the rim of a thin, circular, Keplerian accretion disk truncated at the tidal radius $r_d \simeq (4.9 \times 10^{11}$ cm) / sin i and was calculated by using the mass of the primary and its orbital parameters derived from the radial velocity curve of He II λ4686 (Fig. 3). The hot spot was assumed to be 10° in front of the companion star.

emitted in the irradiated atmosphere of the secondary, but their velocity semiamplitude appears to be larger than K_C. If the emitting region is on a Keplerian orbit, it must therefore be located *inside* the star's orbit.

An alternative possibility is that the N III lines originate from the hot spot where the accretion stream from the star joins the accretion disk, and such an interpretation is indeed consistent with the parameters that we have deduced for this system. The solid line plotted in Figure 4 is not a fit to the data: it is instead the theoretical projected radial velocity of a spot on the rim of the disk, leading the star by 10°. We have assumed here a circular, thin, Keplerian disk truncated at the tidal radius r_d calculated in § 3, and we have made the simplifying assumption that the velocity of the spot will be the vector sum of the systemic velocity, the orbital velocity of the primary with its accretion disk around the center of mass of the system, and the Keplerian velocity of rotation around the primary.

This simple model suggests that the Bowen lines originate either from the hot spot (in that case, the outer edge of the disk must reach the tidal truncation radius) or from the inner part of the accretion stream.

5. CONCLUSIONS

We conclude that the broad He II emission line in GRO J1655−40 shows velocity variations that can be interpreted as being due to the orbital motion of the primary (and hence of its accretion disk). The observed amplitude of the variations allows us to find a 95% confidence limit of $M_X > 5.1\ M_\odot$ for the mass of the collapsed object, thus firmly establishing GRO J1655−40 as a black hole binary system *from its kinematics alone*; this is in good agreement with the mass $M_X = 7.0 \pm 0.2\ M_\odot$ estimated by Orosz & Bailyn (1997). We also notice that while some of the emission lines, such as He II and Hα, are double peaked and likely to come from the whole disk, others, such as the Bowen lines of N III, seem to come from a localized area in the outer region of the disk.

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