Coláiste na hOllscoile
Corcaigh

OPTICAL, ULTRAVIOLET AND X-RAY ANALYSIS OF THE BLACK HOLE CANDIDATE BG GEMINORUM

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ABSTRACT

We present the first high resolution optical spectrum of the black hole candidate BG Geminorum, as well as ultraviolet spectroscopy from the Hubble Space Telescope, and X-ray data from INTEGRAL. Double-peaked emission lines, formed in the accretion disc of this system, are present in the optical spectrum. The velocities associated with the emission lines constrain the radii at which they are generated. Combined with the mass function of the primary, this provides an insight into the nature of the primary in BG Gem. Our analysis suggests disc rotational velocities of ~1000 km s^{-1} in the UV spectra, which would originate at a radius of 0.7 $R_\odot$ from a 3.5 $M_\odot$ object; if real, this would be strong evidence that the primary in BG Gem is indeed a black hole. Intriguingly, the upper limit provided by the INTEGRAL data gives a maximum X-ray luminosity of only ~0.1 % of the Eddington luminosity.

1 INTRODUCTION

BG Geminorum was discovered by Hoffmeister (1933) and Jensch (1938) as a possible RV Tauri star (luminous yellow pulsating supergiant) with an uncertain period of ~60 days. In 1992, Benson et al. (2000) discovered an eclipsing and ellipsoidal variation in BG Gem, with an optical amplitude of 0.5 mag and a period of 91.645 days. Combined with a sinusoidal radial velocity curve for the secondary, this suggested a binary system, with a K0 giant/supergiant secondary feeding material into an accretion disc around the unseen primary. Kenyon et al. (2002) calculated the mass function to be $(3.5 \pm 0.5)\ M_\odot$, greater than the theoretical minimum mass for a black hole, $\sim 3M_\odot$ (Rhoades and Ruffini, 1974). However, because the primary cannot be observed directly (the inclination of the system is close to 90°) it could also be a B star (Kenyon et al., 2002). If confirmed to be a black hole, BG Gem would be the the longest period black hole binary system, by an factor of ~3, as well as being the only known eclipsing black hole binary system in the Galaxy.

One method to investigate the nature of the primary is to acquire higher quality optical spectra, to determine the maximum rotational velocity of the accretion disc surrounding the primary. Large velocities would favour a black hole primary, as ~700 km s^{-1} is the maximum velocity for a disc surrounding a B type star (Kenyon et al., 2002). If the primary in BG Gem is a B star, and it is not obscured by the disc, then UV spectra should show a strong continuum and absorption lines from ionised Si. Detection of broad high ionisation emission lines would favour a black hole. Here, we present the first high resolution optical spectrum of this system, as well as the first UV spectra, and X-ray data from INTEGRAL.

2 DATA

2.1 OPTICAL DATA

We acquired an optical spectrum with the Nordic Optical Telescope (NOT) in La Palma on 2006 April 11. Echelle grism 9 with grism 10 cross disperser on the Andalucia Faint Object Spectrograph and Camera (ALFOSC) instrument were used, giving a resolution of ~1.5 Å, and a dispersion of ~0.6 Å pix^{-1}, over a wavelength range of λλ3300 – 10500 Å. The exposure time was 1200 seconds, using a 1″ slit, giving a signal to noise ratio of ~60. The spectrum was extracted and wavelength calibrated using standard IRAF tasks.

2.2 ULTRAVIOLET DATA

To constrain the exact nature of the primary, Kenyon (2001) acquired UV spectra with the Hubble Space Telescope (HST), on 4 nights between 2001 November and 2002 December. The spectra covered two wavelength ranges (FUV: λλ1200 – 1700 Å, using grism G140L, and NUV: λλ1700 – 3000 Å, using grism G230L), and were acquired using the Space Telescope Imaging Spectrograph (STIS) on HST; the full details are in Table 1.

Date (UT)	Grism	Exp. time (s)	Phase[†]
2001 Nov 14	G230L	390	0.27±0.21
2001 Dec 30	G140L	920	0.77±0.22
2001 Dec 30	G230L	390	0.77±0.22
2002 Jan 21	G230L	390	0.01±0.22
2002 Jan 21	G140L	920	0.01±0.22
2002 Jan 21	G230L	390	0.01±0.22
2002 Dec 07	G140L	920	0.51±0.24
2002 Dec 07	G230L	390	0.51±0.24

[†] Based on the ephemeris of Kenyon et al. (2002)

Table 1: Summary of HST STIS UV observations

2.3 X-RAY DATA

In order to investigate the X-ray emission, we examined archival data from the International Gamma-Ray Astrophysics Laboratory (INTEGRAL). Our X-ray data consist of 20–40 keV mosaics from the INTEGRAL Soft Gamma Ray Imager (ISGRI). The maximum exposure is ~250 ksec, obtained between 2003 February and 2004 October.

3 RESULTS

3.1 OPTICAL SPECTRUM

Existing low quality optical spectra hint at disc rotational velocities of ~2000 km s^{-1} (Kenyon et al., 2002). Confirmation of such velocities with higher resolution and S/N spectra would provide strong evidence that the primary in BG Gem is a black hole (Keplerian velocities of 2000 km s^{-1} would originate at a distance of only 0.17 $R_\odot$ from the centre of a 3.5 $M_\odot$ object). Figure 1 shows double-peaked Hα and Hβ emission lines. The emission in the wings is from material with velocities of $\lesssim$500 km s^{-1}, low enough that the central object could be a main sequence B star; the maximum Keplerian velocity of a disc surrounding a 3.5 $M_\odot$ B V star is ~ 700km s^{-1} (1.5 $R_\odot$ is the typical radius for a 3.5 $M_\odot$ B5 star, Cox 2000).
Based on the ephemeris of Kenyon et al. (2002), the orbital phase during our optical observation was 0.9 ± 0.3, suggesting that the disc may have been partially eclipsed by the secondary. Asymmetries in the peaks in both Hα and Hβ show more emission from the red-shifted peak, suggesting that the secondary is just beginning to eclipse the disc, reducing the blue-shifted emission. The very high inclination angle of the system may mean that high velocity regions (if present) may be difficult or impossible to observe. While detection of high velocity material would confirm the primary to be a black hole, non-detection of such material is not definitive evidence that it is not.

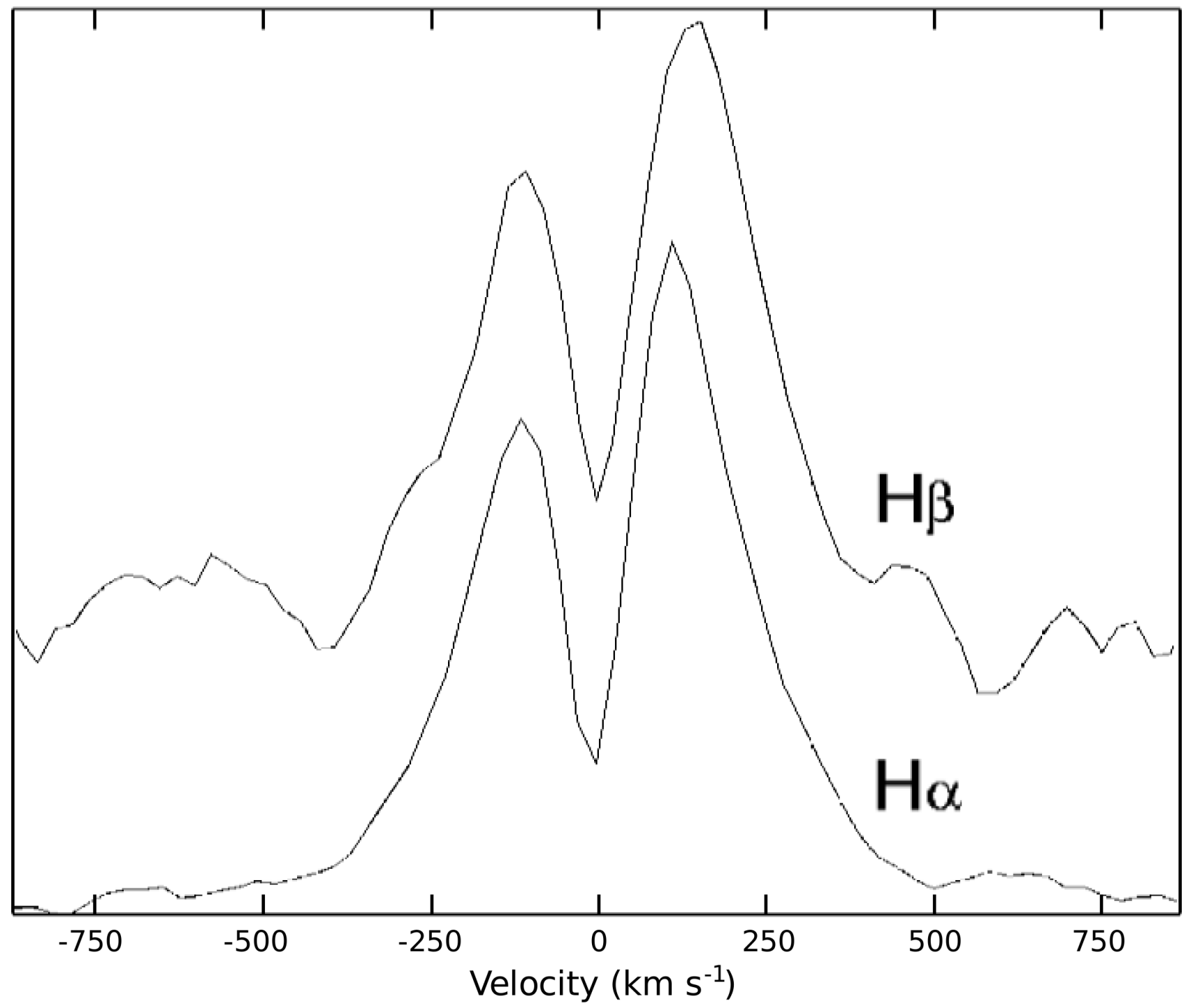

Figure 1: Hα and Hβ emission lines normalised to the local continuum, and offset for clarity

3.2 ULTRAVIOLET SPECTRA

The UV spectra show strong emission lines from Si, Al and Mg ions, with a very weak continuum. Figure 2 shows the merged spectrum from FUV and NUV data from 2001 December 30. Individual lines have emission from maximum velocities as shown in Table 2. Irrespective of the phase during the UV observations, the maximum velocities shown in Table 2 are similar in all the spectra. Because of the large error in the phase, even the observations targeted at phase 0 may have been obtained away from eclipse.

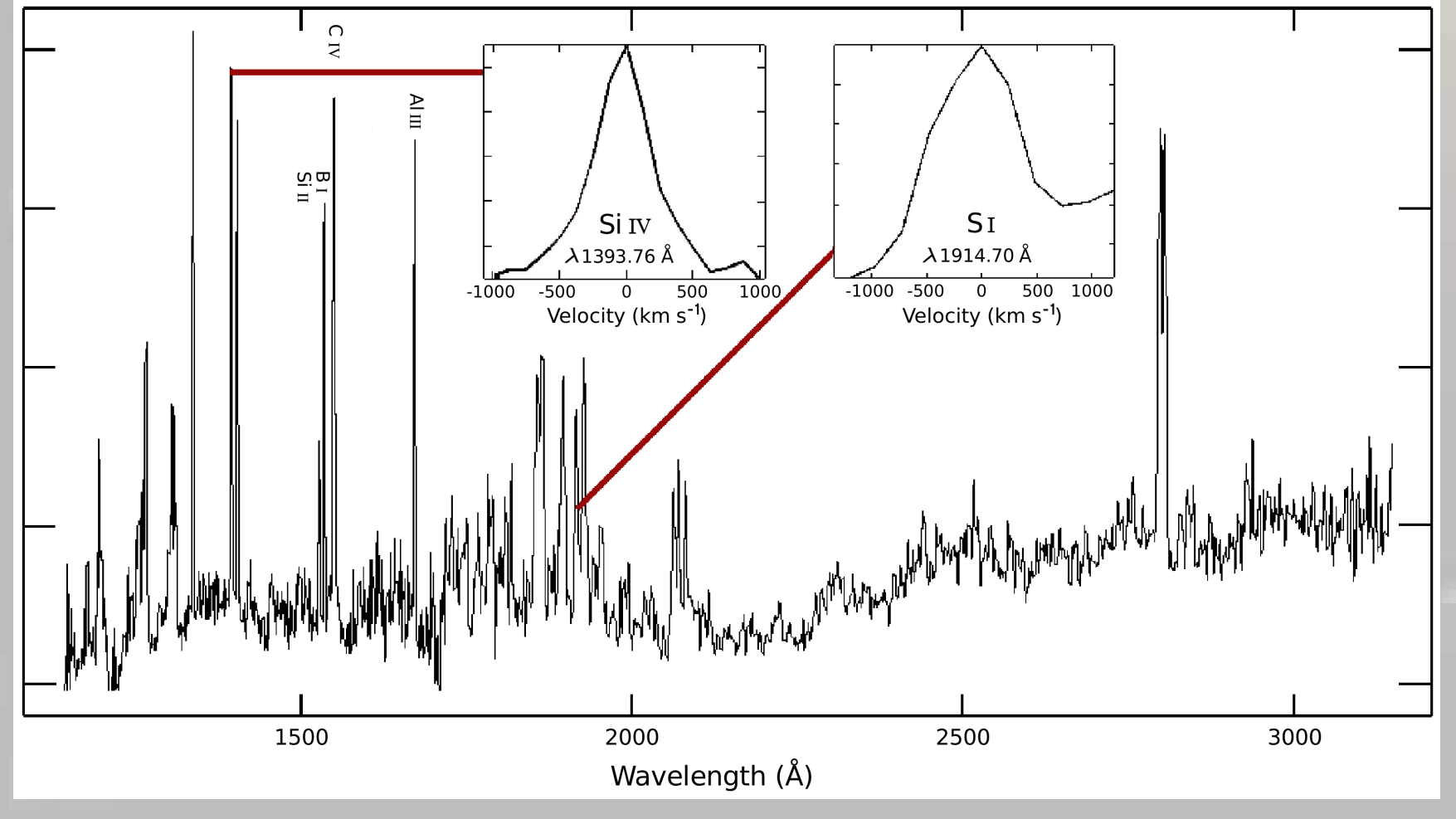

Figure 2: Combined spectrum for FUV and NUV data acquired on 2001 December 30. The insets show the Si IV line at λ1393.76 Å and the S I line at λ1914.70 Å plotted against velocity of emission.

Ion	λ (Å)	Max. velocity (km s^{-1})
S I	1914.70	~1000
Si IV	1393.76	~700
C IV	1548.2, 1550.77	~650, ~650
Si II	1526.70	~600
B I	1533.81	~600
Al III	1670.79	~500

Table 2: Maximum emission velocity for various lines in the UV spectra

According to Kenyon et al. (2002), Si II and Si III absorption lines would be an indication that the primary is a B star. Another signature would be a strong UV continuum. Neither of these are evident in the spectra. Gänsicke et al. (2005) present optical and UV spectra for 3 Dwarf Novae (DNe). In each of these, the optical spectra display double-peaked emission lines, while the UV spectra show single peaked, broad emission lines – similar to BG Gem. This is likely due to the reduced velocity resolution at UV wavelengths (e.g. 1.5 Å resolution at Hα is equivalent to ~70 km s^{-1}, whereas at 1500 Å, this translates to 300 km s^{-1}). In the case of BG Gem, the peak-to-peak separation at Hα is ~240 km s^{-1}, a similar separation in the UV would not be resolved with a spectral resolution of 1.5 Å, leading to the appearance of a single peak.

3.3 X-RAY RESULTS

BG Gem is relatively near the Crab pulsar, which affects the background estimation for the ISGRI observations. At the position of BG Gem, the measured flux due to this background is ~0.1 cps, which we take as an upper limit to the flux of BG Gem. One advantage of having the Crab in the field of view is that we can directly compare the two – in the same mosaic image the Crab is 103 cps, so BG Gem is ≤1 mCrab in the 20–40 keV range. Assuming a spectrum similar to that of other X-ray binaries, this translates to $\sim 10^{-12}$ ergs $cm^{-2}\ s^{-1}$, or X-ray luminosity (L_X) $\leq 10^{33}$ ergs s^{-1} at a distance of 2.25 kpc.

4 DISCUSSION

Based on the mass function, mass ratio ($q \equiv M_2/M_1$) and inclination angle (Kenyon et al., 2002), along with the maximum velocities observed in the optical spectrum, the primary could be a B8 V star, or a black hole. If the higher velocity material seen in the UV spectra is real, then the primary must be a black hole, as no normal star has a mass of 3.5 $M_\odot$ and a maximum radius of 0.7 $R_\odot$ (Cox, 2000). If the accretion disc entirely obscures the primary, then it is impossible to determine the nature of the primary based on comparison of the spectra with standard atlases. Given the high inclination of the system, this is a plausible scenario. The secondary is classified as being a K0 supergiant (Benson et al., 2000), based on comparison of the observed spectra during primary eclipse with standard spectral atlases. This would imply an M_V of ~-6 (Cox, 2000), giving a distance to BG Gem of ~30 kpc, which is unlikely. In fact, in their distance calculations, Benson et al. (2000) choose a value for M_V of ~-0.4, typical of a K0 giant. Furthermore, based on the maximum mass of the primary of $\lesssim 5\ M_\odot$, and a q of ~0.22 (Kenyon et al., 2002), this would mean the mass of the secondary is at most ~1 $M_\odot$. Combined with the estimate of the radius of the secondary, ~40 $R_\odot$, it appears to be closer to a giant than a supergiant.

Comparing BG Gem with DNe, the appearance of the UV spectrum of DNe at outburst maximum is strongly correlated with inclination angle (la Dous, 1991). At low inclinations, there is almost pure absorption, transitioning to strong emission as the inclination angle approaches 90°. VY Hyi is a low inclination system, showing a strong blue continuum with high ionisation lines in absorption (Harlaftis et al., 1992). OY Car, an eclipsing DN, has a relatively cool UV continuum with strong, broad emission lines (Naylor et al., 1988), similar to BG Gem.

Benson et al. (2000) report that the average of 100 days of data from the All-Sky Monitor (ASM) on the Rossi X-ray Timing Explorer (RXTE) is −0.1 ± 1.0 mCrab at 2–12 keV. At a distance of 2.25 kpc, this gives an upper limit to L_X of $\sim 10^{34}$ ergs s^{-1} (taking 1 mCrab as the flux). Assuming that an accretion disc corona scatters ~1% of X-rays into the line of sight (White et al., 1981), the upper limit to the intrisic L_X seen in the INTEGRAL data is approximately an order of magnitude less than that reported by Benson et al. (2000), or $\lesssim$0.1 % of the Eddington luminosity. However, it is worth noting that the INTEGRAL and RXTE data are from different epochs, and over different energy ranges. If the primary is a black hole, then the upper limit on L_X suggests that it is in quiescence, and X-ray reprocessing cannot be responsible for the observed disc brightness – it must be entirely due to viscous heating.

The lack of high ionisation emission (e.g. He II λ4686 Å) supports this. Benson et al. (2000) estimate that the disc contributes ~10% of the optical flux, based on light curve analysis. With their values for extinction (A_V = 1.65), distance (2.25 kpc) and V band magnitude (13), the accretion disc has M_V ~2.1. Using the relationship of Smak (1989), this gives an accretion rate through the disc of $\sim 10^{-6}\ M_\odot\ yr^{-1}$. However, beacause of the low L_X, this material cannot be accreting onto the primary, and so must be accumulating in the disc. Furthermore, this high accretion rate, coupled with the mass estimate of the secondary of $\lesssim$1 $M_\odot$, means a short lifetime for this system.

Our data are not of sufficient quality to definitively constrain the nature of the primary. Our optical spectrum may have been acquired when the primary/centre of the disc was partially eclipsed. The UV spectra suggest disc velocities of up to 1000 km s^{-1}, but the resolution is insufficient to say for sure if this apparent high velocity emission is from the central line, or is contamination from neighbouring lines. It is possible that the high velocity central regions are permanently obscured by the disc edge. However, if the emission at 1000 km s^{-1} is real, then even this would be strong evidence that the primary is a black hole.

4.1 FUTURE WORK

Echelle optical spectroscopy over the full orbital period would ensure that we acquire spectra away from eclipse, allowing us to investigate the maximum velocities present in the disc for the Balmer lines. Regardless of whether we observe the higher velocity material, these data will allow us to construct Doppler tomograms (Marsh, 2001) from the Hα and Hβ lines. This would be the first Doppler tomography performed on an accretion disc in a system with such a large period, regardless of the nature of the primary. High resolution UV echelle spectroscopy would clarify if the apparent high velocity emission is real. Chandra or XMM observations of this system would provide a much more accurate determination of the X-ray luminosity.

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S. E. Shaw is currently with the INTEGRAL Science Data Centre in Switzerland.

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