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2010 J. Phys.: Conf. Ser. 218 012028

(http://iopscience.iop.org/1742-6596/218/1/012028)

Journal of Physics: Conference Series **218** (2010) 012028 doi:10.1088/1742-6596/218/1/012028

Looking into the heart of a beast: the black hole binary LS 5039

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Abstract. LS 5039 is a relatively close microquasar consisting of a late O-type star and a compact object (very possibly a black hole) on a highly eccentric orbit with a period of 3.9 days. The high X-ray, gamma-ray and radio luminosity indicate light-matter interaction, which arise from the stellar wind of the primary star accreting toward the black hole. Former examinations suggest that LS 5039 could be a prototype of wind-fed high mass X-ray binaries (WXBs) with diskless main sequence O primaries. Now there is a great chance to better understand the configuration and the physical processes in the exotic system. In July 2009 LS 5039 was followed by the Canadian MOST space telescope to get ultraprecise photometric data in a month-long semi-continuous time series. Parallel to this, we have taken simultaneous high-resolution optical spectra using the 2.3m ANU telescope of the Siding Spring Observatory, supplemented with further data obtained in early August 2009 with the same instrument. Here we present the first results from the new echelle spectra, which represent the best optical spectroscopy ever obtained for this intriguing system. We determined fundamental orbital and physical parameters of LS 5039 and examined the configuration and the circumstellar environment of the system via radial velocity measurements and detailed line-profile analysis of H-Balmer, He I and He II lines.

1. Introduction

LS 5039 (V479 Sct), classified as a high-mass X-ray binary (HMXB) by Motch et al. (1997), is one of the most studied members of its class. Based on VLA data, Martí et al. (1998) discovered a persistent non-thermal radio counterpart, associated with mildly relativistic radio jets (Paredes et al. 2000, 2002). In addition, a very high energy (VHE) γ-ray source was also found by the CGRO/EGRET (Paredes et al. 2000) and HESS (Aharonian et al. 2005) surveys. The observed features make LS 5039 a prominent member of the so-called gamma-ray binaries.

The optical companion of the system is a bright (V = 11.2), O6.5V((f)) type star classified by Clark et al. (2001) and McSwain et al. (2001, 2004). McSwain et al. (hereafter M04) presented the first orbital parameters of the binary system. Casares et al. (2005; hereafter C05) performed a detailed spectroscopic analysis of LS 5039, and calculated a new set of orbital and

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physical parameters. They found an orbital period of 3.906 days, which has been confirmed by other studies: for example, variability also in X-rays (Bosch-Ramon et al. 2005, Takahashi et al. 2009), at GeV (Abdo et al. 2009) and TeV energies (Aharonian et al. 2006) occurs with the same period, suggesting orbital modulation of the high-energy emissions. Very recently, Aragona et al. (2009; hereafter A09) – using the old and some new RV points – also confirm the value of the orbital period and refined the parameters.

We have organised a simultaneous campaign of MOST space photometry and ground-based optical spectroscopy, which was executed in July 2009. The main goal of the project was an investigation of the system parameters (based on a new, independent, high-resolution data set), as well as an attempt to detect clumpiness in the stellar wind of the O-type star. Here we report on the first results of our spectroscopic analysis, while the detailed discussion of the results of the coordinated campaign will be presented elsewhere (Sarty et al., in prep).

2. Observations and data reduction

Spectroscopic observations were carried out on four nights between 2009 July 8-11 (parallel to MOST observations) and on three nights between August 1-3, using the 2.3-m telescope of the Australian National University (ANU) equipped with an echelle spectrograph. In total, the obtained 118 spectra cover almost 40 hours and ensure a good sampling of the whole orbit. The integration times were between 900-1200 s, while the spectra covered the whole visual range between 3900 Å and 6720 Å . The nominal spectral resolution is $\lambda/\Delta\lambda \approx 23\,000$ at the Hα line, with typical SNR of about 100 in 1 hour integration.

All data were reduced with standard IRAF[1] tasks, including bias and flat-field corrections, cosmic ray removal, extraction of the 27 individual orders of the echelle spectra, wavelength calibration, and continuum normalization.

3. Analysis and results

3.1. Radial velocities

To measure radial velocities we first generated one hour long average spectra to get higher S/N – one hour corresponds to 0.01 orbital phase, hence negligible phase smearing appears in the phased radial velocity data. The data were phased with an orbital period of 3.906 days (C05) and our RV curve confirms that this is indeed the correct value.

To generate the final RV diagrams we used average velocities of H I (Hα, Hβ, Hγ, Hδ, λ3835), He I (λ4471, λ5875) and He II (λ4200, λ4686, λ5411) lines; there are several other H and He lines in the wavelength region of our spectra, but they were too noisy or blended to use them for velocity determination. The typical measurement error is $\pm$10-15 km s^{-1}, which is partly caused by the observational noise, partly by the large rotational velocity of the O-type star ($v \sin i = 113 \pm 8$ km s^{-1}, C05).

Our results indicate that there is a large systematic shift between He II, He I and H Balmer lines: the H I and He I lines are always blueshifted by about 20 km s^{-1} in respect to the He II lines, which is a characteristic signature of a strong stellar wind. The photosphere of the O-type star is too hot for the H I and He I lines ($\approx$ 40 000 K), hence these are generated in the cooler outer regions. Interestingly, this velocity difference between the different species and ionisation states has not always been taken into account: C05 also examined this effect (but they found smaller differences between velocities), but it was simply neglected by A09.

We also measured equivalent widths of several interstellar lines to estimate the rate of interstellar reddening (see Section 3.2). During that we found redshifted satellite absorptions in the Ca II K and Na I D1& D2 lines with a radial velocity around +60 km/s (more precisely,

[1] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

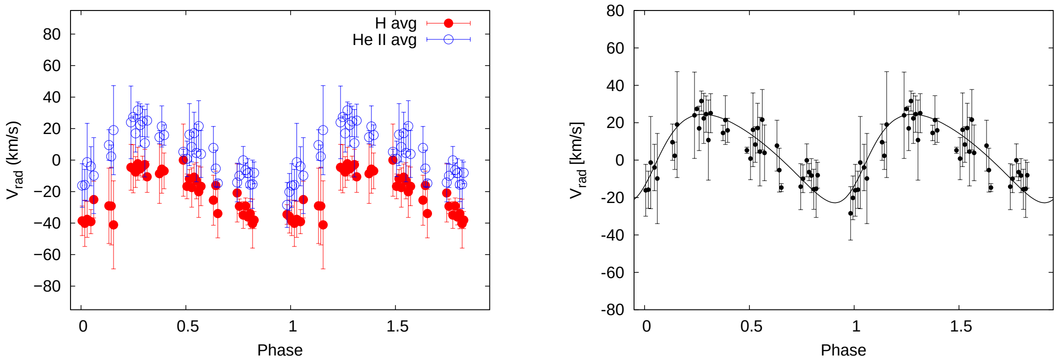

Figure 1. *Left*: Radial velocities based on H Balmer and He II lines. *Right*: The best-fitting curve to radial velocities of He II lines.

+58.4 ± 2.2 km s^{-1} by Ca K, +62.9 ± 2.3 km s^{-1} by Na D1 and +61.9 ± 1.7 km s^{-1} by Na D2). These satellite lines may belong to a formerly unknown galactic Intermediate Velocity Cloud (IVC; see a review in Wakker & van Woerden 1997).

3.2. Orbital and physical parameters

In the following analysis we adopted $T_{\rm eff}$ = 39 000 ± 1000 K and log g = 3.85 ± 0.10 for the stellar companion (C05). To determine interstellar reddening we used Na I D1 (EW = 0.70 ± 0.02 Å ; see for ref. Munari & Zwitter 1997), DIB λ5780 and DIB λ6613 (EW = 0.55 ± 0.05 Å and 0.18 ± 0.02 Å , respectively, see for ref. Cox et al. 2005, Fig. 4.) lines, and we have got $E(B-V)$ = 1.2 ± 0.1, which is in very good agreement with previous results (Ribó et al. 2002, M04). Using other photometric parameters (R, M_v, see C05 and references therein) we also confirmed the distance (d = 2.5 ± 0.1 kpc), stellar radius ($R_0 = 9.3^{+0.7}_{-0.6}$ R$_\odot$) and mass of the O star ($M_0 = 22.9^{+3.4}_{-2.9}$ M$_\odot$) published by C05.

Radial velocity curves were modelled using the 2003 version[2] of the Wilson-Devinney (WD) code (Wilson & Devinney 1971, Wilson & van Hamme 2003). We note that during the analysis we only used our own velocity points, which are independent from any previous data in the literature, and constitute the highest resolution, homogenous spectral dataset ever used to get the orbital solution of LS 5039.

The determined orbital parameters are shown in Table 1, compared to results of C05 and A09. The ones published by C05 were based only on velocity points related to He II lines, while A09 combined the velocities of every available H, He I, and He II lines (see our cautionary notes above).

In general, our parameters are close to previous solutions, but there are some differences. The value of V_γ is definetly higher in C05 than in A09 or in our paper. The possibility of a real change in this parameter during only some years is very small, so the reason of the difference could be effect from different data treatment in of C05. The other important difference is our smaller value of e, what we explain with the smaller scatter and better coverage of our dataset.

[2] ftp://ftp.astro.ufl.edu/pub/wilson

Table 1. Orbital parameters of LS 5039.

Parameter	C05 (He II)	A09	This paper (He II)
T_0 (HJD−2450000)	1943.09 ± 0.10	2825.99 ± 0.05	5017.08 ± 0.06
P_{orb} (d)	3.90603	3.90608	3.906 (adopted)
e	0.35 ± 0.04	0.34 ± 0.04	0.24 ± 0.08
ω [°]	225.8 ± 3.3	236.0 ± 5.8	237.3 ± 21.8
V_γ [km s^{-1}]	17.2 ± 0.7	4.0 ± 0.3	3.9 ± 1.3
K_1 [km s^{-1}]	25.2 ± 1.4	19.7 ± 0.9	23.6 ± 4.0
a_1 sin i [R$_\odot$]	1.82 ± 0.10	1.44 ± 0.07	1.77 ± 0.15
$f(m)$ [M$_\odot$]	0.0053 ± 0.0009	0.0026 ± 0.0004	0.0049 ± 0.0006
rms of fit [km s^{-1}]	9.1	7.1	6.2

3.3. Circumstellar matter

To infer mass loss rate of the O star and the properties of the circumstellar matter, we determined the equivalent widths of each H and He line and also their variability during the orbit, which could be a good indicator of the physical processes taking place in the stellar wind. We executed the measurements on the average spectra summarized from one hour long exposure times, but we plotted the daily average values of *EW*s on final diagrams (to better see the trends).

For the Hα line we found that *EW* changes between 2.50 and 2.85 Å , and its variability shows a weak correlation with the orbital period. The main averege value (2.70 ± 0.12 Å) agree within uncertainties with the result of C05 (2.8 ± 0.1 Å), except that they found that value is stable during the orbit of the binary (which reason could be the relatively low resolution of their spectra). Our result is also consistent with the *EW* values measured in last ten years (Bosch-Ramon et al. 2007). Using the results of Puls et al. (1996, and references therein) we could estimate the mass loss rate from *EW* of Hα line. To do these calculations we also had to use some other parameters: $R_0 = 9.3^{+0.7}_{-0.6}$ R$_\odot$ and $T_{\rm eff}$ = 39 000 ± 1000 K of the O star (C05), terminal velocity (V_∞ = 2440 ± 190 km s^{-1}, M04) and wind velocity law exponent (β = 0.8, M04). We found that the mass-loss rate of the stellar companion is around 3.7 × 10^{-7} M$_\odot$ yr^{-1} by largest absorption (which correspond with the lower limit), while we could give 4.8 × 10^{-7} M$_\odot$ yr^{-1} for upper limit. These values also confirm the results of C05.

There are two lines (Hβ and He I λ5875) by which the values of *EW* are more strongly modulated by orbital period. The lowest absorption is around φ ∼0.75 by H lines, and φ ∼0.65 by the mentioned He line (Fig. 2, left side), close to the expected phase φ ∼0.7 when the compact object is between us and the stellar companion (inferior conjunction).

By H Balmer lines we also tried to determine the phase dependence of *EW*s only of emission components. Because of the relatively small S/N it was not performable to follow hour-to-hour changes in line profiles, so therefore we generated difference spectra subtracted Doppler-corrected daily average spectra from their main average to calculate *EW*s of remaining emission components. Using these values quantitatively would be an excessive implementation of results, but the relative, phase dependent changes are examinable.

The three diagrams (Fig. 2, right side) are very similar to each other, with a significantly exceeding point (which means maximal emission here) near inferior conjunction (φ ∼0.65). It agrees with the diagrams shown on the left side of Fig. 2, where lowest absorption is also at that phase. We can rule out any technical artifacts which could produce the similarity of the three diagrams, because the lines are in different echelle orders, so they went independently through the different steps of data reductions.

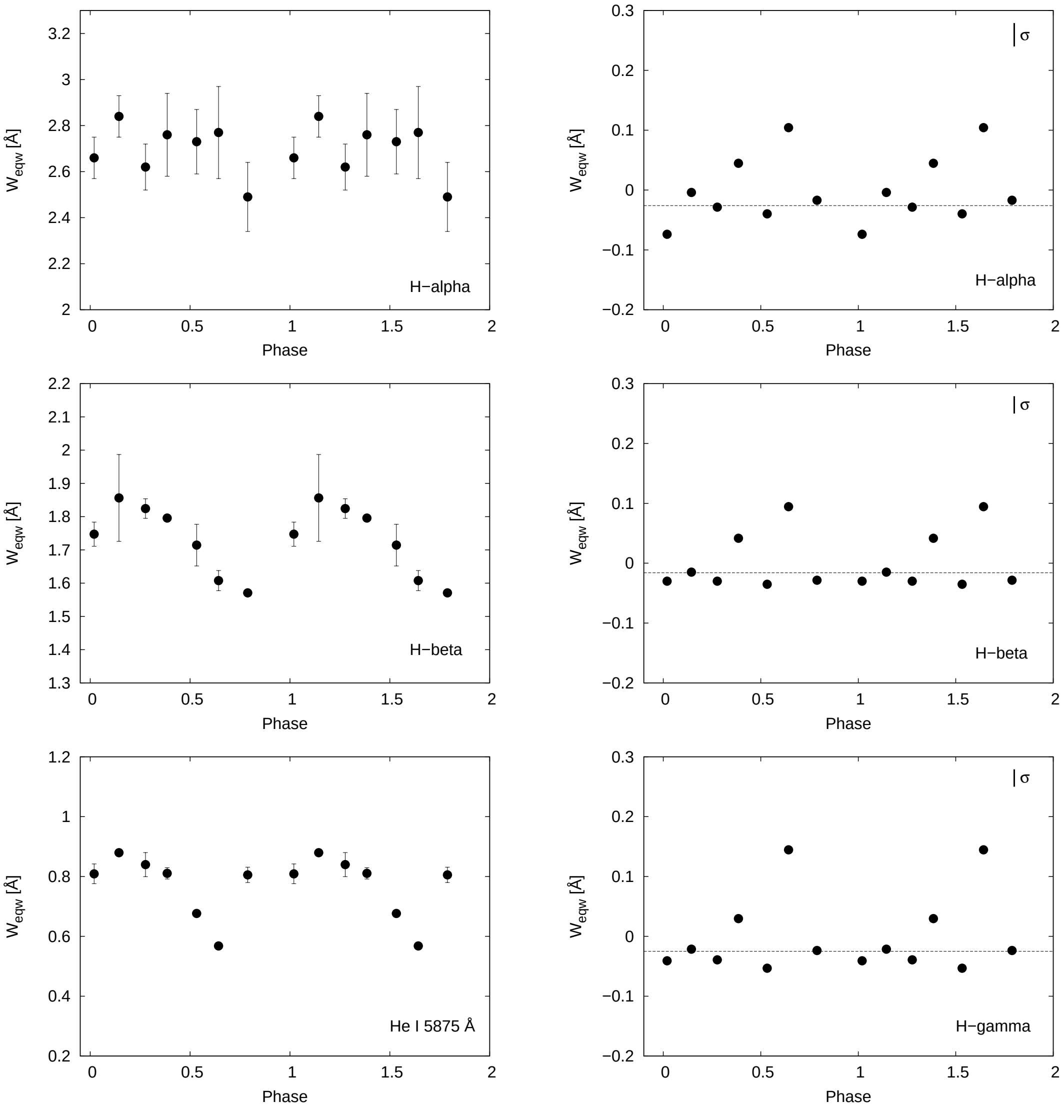

Figure 2. *Left*: Variability of equivalent widths of Hα, Hβ and He I λ5875 lines during the orbit. *Right*: Variability of equivalent widths of the emission components of Balmer lines during the orbit of LS 5039. In these diagrams larger numbers correspond to larger emission rates. There is a point by each line with a significantly high value (3, 3 and 5 σ above average, respectively) at φ ~0.65.

4. Summary

In our work we presented the first results of a coordinated campaign consisting of parallel space photometry and high-resolution ground-based spectroscopy of the the X-ray (gamma-ray) binary LS 5039. Detailed analysis of spectroscopic data (which incarnate the highest resolution, homogenous dataset ever obtained from that object) allowed us to determine the orbital parameters of the system being mainly consistent with former solutions, but we also found some differences (emphasizing the significant velocity shift between H I, He I and He II lines, and the smaller value of eccentricity).

To reveal the properties of the circumstellar environment, we first measured the equivalent widhts of available H and He lines during the orbit. We found that Hα, Hβ and He I λ5875 lines are unambiguously modulated by orbital period – the clear emission components of H Balmer lines show similar phase dependence, which seems to confirm that it is a real effect. From the average EW of Hα line we estimated the mass loss rate of the O star and got similar value to former results.

The complete analysis of our observations about LS 5039 will be presented in a latter paper (Sarty et al., in prep), including discussion about the circumstellar environment and possible mass ranges of the compact object.

Acknowledgments

This work has been supported by the Australian Research Council, the University of Sydney, the Hungarian OTKA Grant K76816 and the "Lendület" Young Researchers' Program of the Hungarian Academy of Sciences.

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