Mass and orbit constraints of the gamma-ray binary LS 5039

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I. LS 5039: an enigmatic binary

LS 5039 was originally classified as a high-mass X-ray binary (HMXB, Motch et al. 1997) which has been intensively observed in the radio, optical/IR, UV and gamma-ray wavelengths in the past years. Paredes et al. (2000) identified relativistic jets in VLBA observations. They also found a **very high energy (VHE) gamma-ray source** at the coordinates of the system (reidentified by Aharonian et al. 2005 in a HESS survey); therefore LS 5039 became one of the several known gamma-ray binaries.

McSwain et al. (2004) showed that the primary is a O6.5((f)) star, while orbital and system parameters were published in different papers (Casares et al. 2005 – C05; Aragona et al. 2009 – A09; and in our paper, Sarty et al 2011 - S11). One of the major question about LS 5039 is **the nature of the compact object**: while analysis of C05 suggests that the compact object is a **black hole**, some other authors have argued for a neutron-star scenario involving a **non-accreting young pulsar** (see S11 for a review). The situation is further complicated by some results indicating that the high energy radiation might originate from regions far outside the orbit of the binary (see references in S11, and more recently Durant et al. 2011).

Hereinafter we show the results (published most of them in detail in S11) of our spectroscopic and photometric analysis concerning mass and orbit constraints of LS 5039 and studying of stellar wind of the O component.

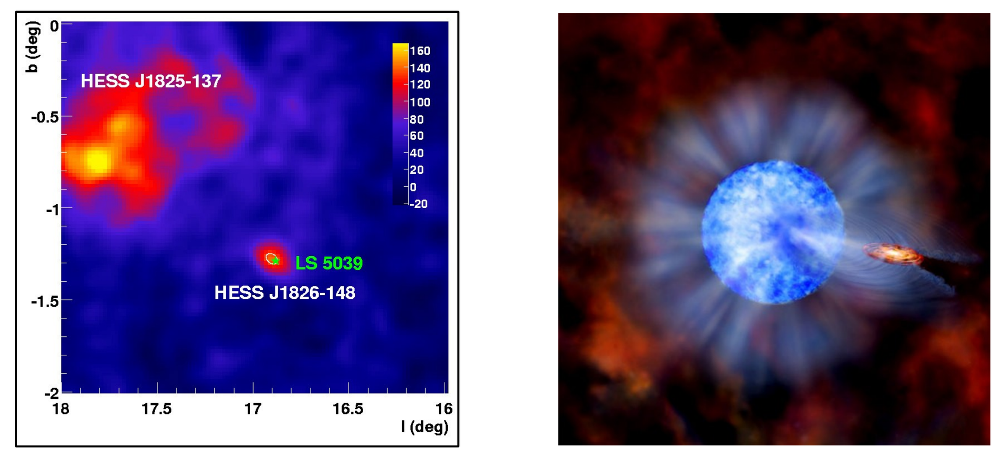
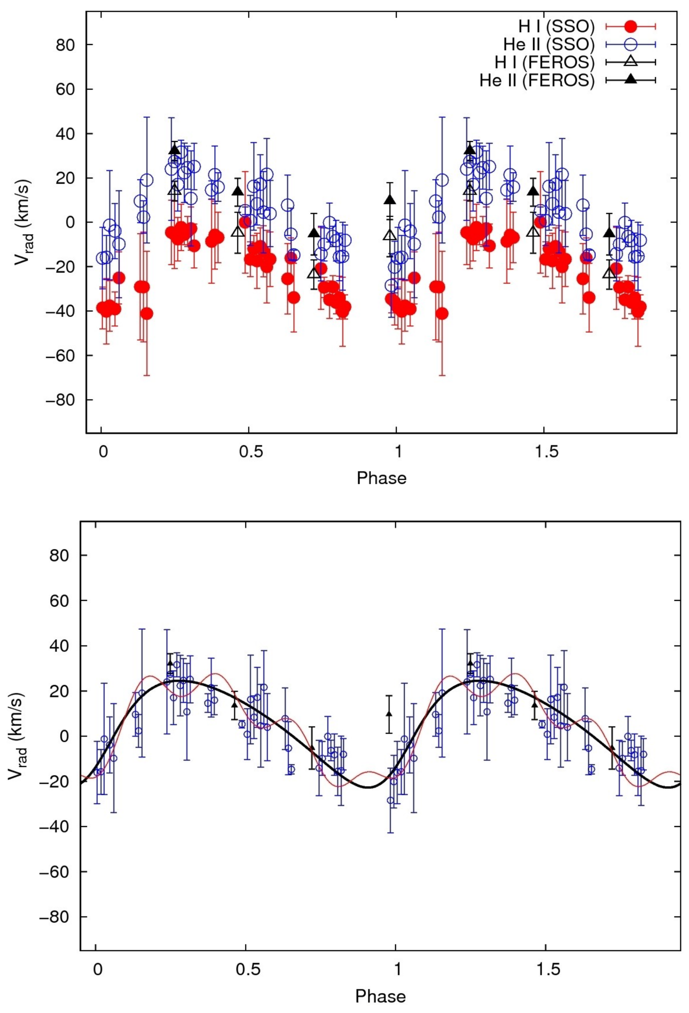


Fig.1. *Left:* Region of LS 5039 as seen by HESS gamma-ray telescopes (Aharonian et al. 2005). The green asterisk and the small white ellipse show the radio coordinates of LS 5039 and the position of the VHE gamma-ray source, respectively (www.pm.rub.de).
Right: Illustration of an X-ray binary containing a hot star and a black hole (NASA/CXC/M. Weiss).

II. Radial velocity analysis

Spectroscopic observations were carried out on seven nights in 2009 with the echelle spectrograph mounted at ANU 2.3m Telescope (SSO, Australia), and on four nights in 2011 using FEROS (Kaufer et al. 1999) at MPG/ESO-2.2m telescope at La Silla, Chile. Covering ~40 hours with nearly uniform sampling of the whole orbit between 3900-6750 Å with a resolving power $\lambda/\Delta\lambda \approx 23{,}000$ at Hα, it is **the highest resolution, homogeneous spectral dataset** ever obtained for LS 5039.



Radial velocities (RV) of H I, He I and He II lines were determined from the shifts of line centroids with respect to the laboratory wavelengths. We detected **a ~15-20 km s^{-1} blueshift** between the average RVs of the He II and the Balmer lines, while the RVs of the He I lines are between them. We assume that the shift of the H I and He I lines is due to contamination from stellar wind (see Puls et al. 1996). Therefore we used only the RVs of He II lines to fit eclipsing binary models using the 2003 version of Wilson-Devinney (WD) code (Wilson & van Hamme 2003).

Orbital and system parameters are presented in Section 3. Our analysis **do not support** the results of Casares et al. (2010) detecting the signs of non-radial pulsations of the O star in their RV data.

Fig.2. *Top:* Average radial velocities of H I (Hα, Hβ, Hγ, Hδ, λ3835 – the latter two were used only by SSO spectra) and He II (λ4200, λ4686, λ5411) lines. *Bottom:* The best-fitting curve to radial velocities of He II lines (black line) and the model of Casares et al. 2010 showing the assumed signs of pulsations of the O star (red line).

III. Orbital and system parameters

Based on equivalent width measurements of several interstellar lines we found E(B−V) = 1.2 ± 0.1 mag, which agrees well with previous results (S11). Therefore we adopt the distance of LS 5039 as well as the orbital period and the parameters of the O component obtained by C05.

The value of T_0 = HJD 2455017.08 was used as the epoch of periastron. Our results are close to previous solutions (C05, A09), but **we found the orbital eccentricity being definitely lower** than determined previously. This smaller value is **more consistent with the lack of an accretion disk** around the compact object (see S11 for the details).

Because LS 5039 is a single-lined spectroscopic binary, we were able to determine only the mass function, *f(m),* instead of the exact value of the mass ratio (*q*) and the inclination (*i*).

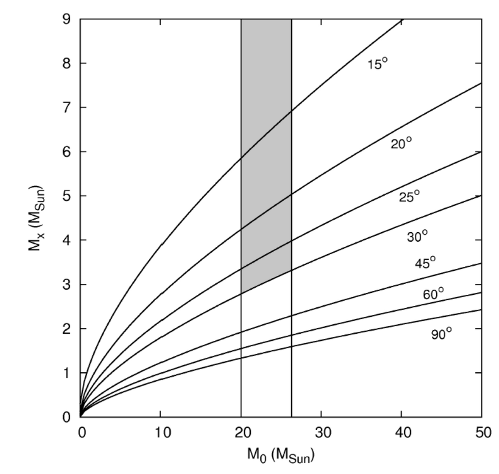


Fig.3. Mass of the compact object as a function of mass of the primary for different inclinations. Vertical lines show the limits of the mass of the O star, gray region represents the possible values of the compact object in the case of $i < 30^{\circ}$ prefer by C05 (see S11).

T_{eff} (K)	39000 ± 1000
$\log g$	3.85 ± 0.10
R_0 ($R_\odot$)	$9.3^{+0.7}_{-0.6}$
M_0 ($M_\odot$)	$22.9^{+3.4}_{-2.9}$
d (kpc)	2.5 ± 0.1
P_{orb} (d)	3.906

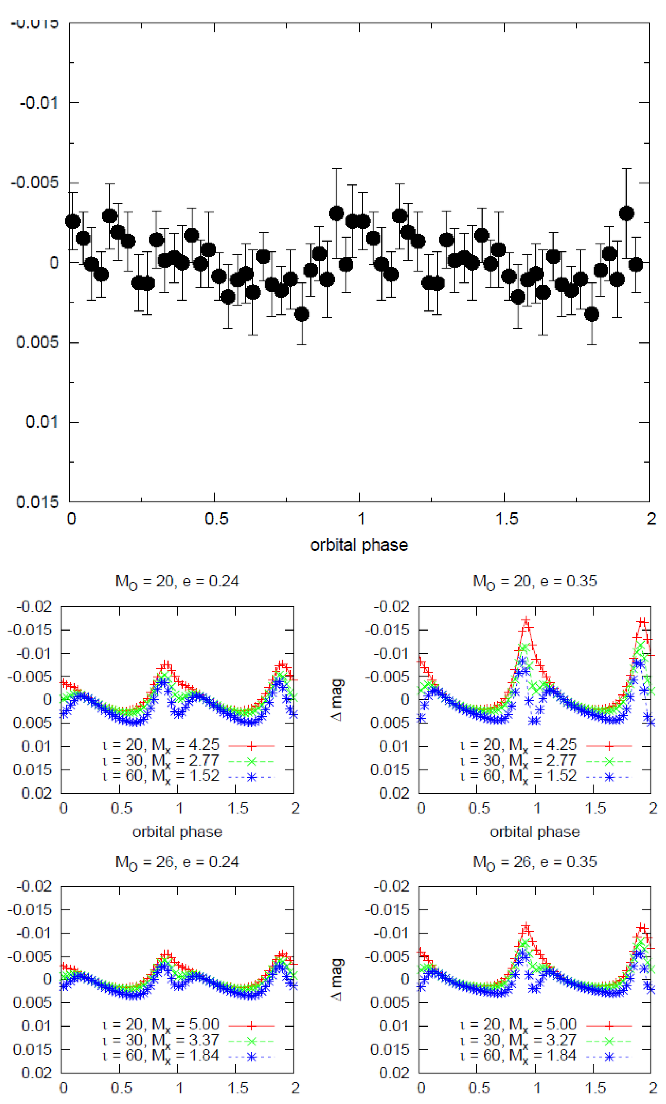
Table 1. Adopted parameters from C05.

e	0.24 ± 0.08
ω (°)	237.3 ± 21.8
V_γ (km s^{-1})	3.9 ± 1.3
K_1 (km s^{-1})	23.6 ± 4.0
$a_1 \sin i$ ($R_\odot$)	1.77 ± 0.15
$f(m)$ ($M_\odot$)	0.0049 ± 0.0006
RMS of fit (km s^{-1})	6.2

Table 2. Orbital parameters of LS 5039.

IV. Mass constraints from *MOST*-photometry

Beyond the spectroscopic dataset we also studied the photometric data from the *MOST* satellite obtained through 16 days in July, 2009. Based on light curve simulations **C05** found that **if photometric variability is less than 0.01 mag** then **the inclination is 30º or less** which implies than **the mass of the compact object is too high to be a neutron star** (see Fig. 3.).



The *MOST* light curve indicates **only a possible variability at the level of 2 mmag**, with an apparent broad minimum at phase φ ~ 0.7 – 0.8.

We did our own light curve simulations with the WD code as a check. Our conclusions **differ from the ones of C05**. **With the mass function fixed, the amplitude of the light curve do not decrease with decreasing inclination**. Instead, the **amplitude decreases** with **increasing total mass** or **decreasing eccentricity**. A formal fit gave the best result as M_0=26 M_{Sun}, e=0.24 and i=60º (M_x=1.84 M_{Sun}).

Our results strengthen the black hole scenario, but do not fully exclude that the compact object may be a neutron star.

Fig.4. *Top:* Phased and binned light curve from the *MOST* observations. Δmag values represent the magnitude difference from the mean brightness. *Bottom:* Model light curves calculated with $f(m)$=0.0049 M_{Sun}. M_0 and M_x are the masses of the primary and the compact object, respectively, i is the inclination in degrees.

V. Stellar wind from the O component

Changes in the equivalent widths (EW) of H and He lines could be good indicators of physical processes taking place in the stellar wind.

We found that the EW of **Hα** is changing from 2.50 to 2.85 Å over the orbital cycle. The average value of 2.70 Å agrees well with previous results (C05, Bosch-Ramon et al. 2007). Using the method of Puls et al. (1996) we got 3.7 – 4.8 · 10^{-7} M_{Sun} yr^{-1} for the mass loss rate of the O star.

We found two other lines, **Hβ** and **He I λ5875, showing significant EW changes during the orbit**. The weakest absorption (lowest EW) occurs around φ ~ 0.65 – 0.75 (**at inferior conjunction**). A possible explanation may be the **focusing of the stellar wind toward the compact object** (S11).

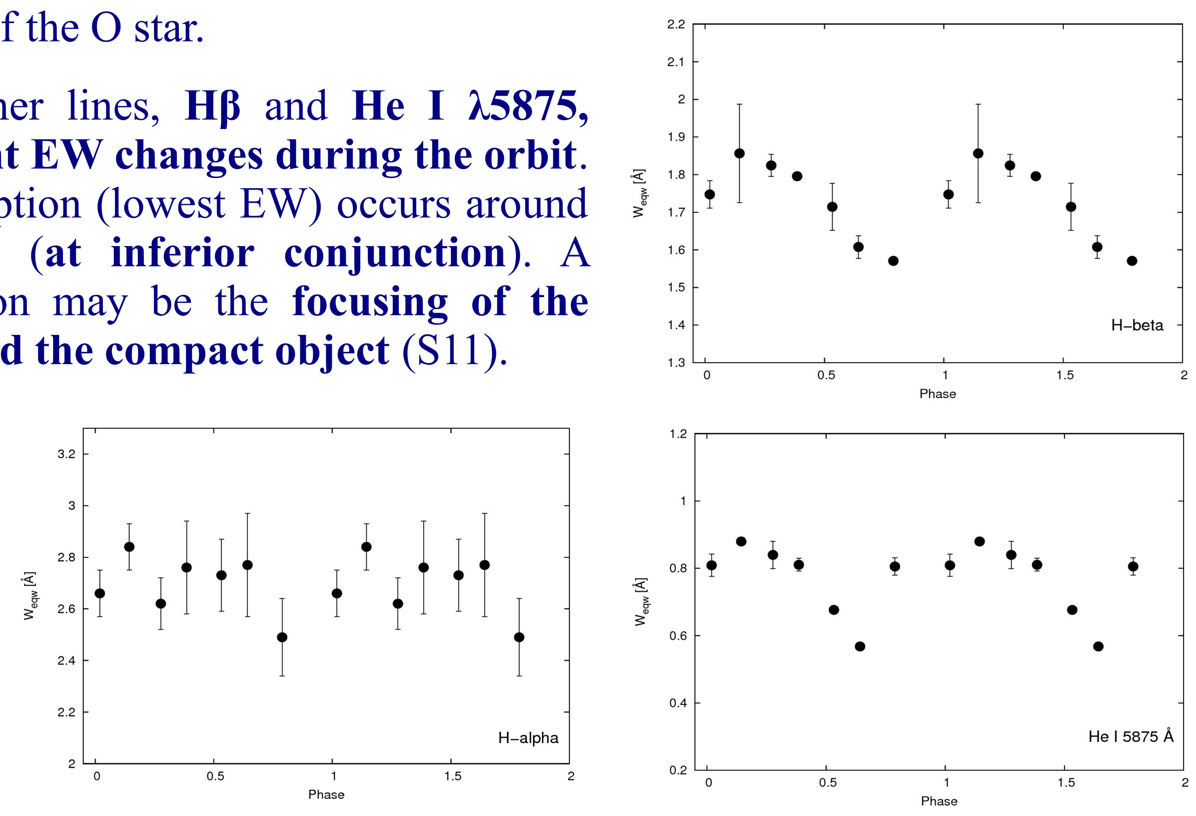


Fig.5. Variability of the equivalent widths of Hα (bottom left), Hβ (top right) and He I λ5875 (bottom right) lines during the orbital cycle.

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Questions? Comments?
Please let me know!

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