The asymptotic evolution of the blue straggler star V1309 Sco

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Introduction to V1309 Sco: A probable blue straggler in the making

Those systems composed of a dwarf late-type K or M star (called secondary) and a white dwarf (primary star) are called cataclysmic variables stars (CVs; Warner 2003), characterised by a continuous mass transfer from the secondary to the surface of the primary star when the secondary fills its Roche Lobe. This mass transfer can be irregular if the primary star has a very active magnetic field, which apparently is not observed in the case of V1309 Sco. Furthermore, as both stars are moving, the matter has angular momentum $\mathbf{L} \neq 0$, an accretion disk around the primary star is expected to be formed. Some of those systems can evolve until be able to share the same gaseous envelope. In this case, they are called *contact binary stars*, predicted to be common in our Galaxy, especially in globular clusters, however not efficiently found. V1390 Sco was originally identified during a nova event in 2008, where its likely progenitor was an eclipsing binary system with an initial orbital period P = 1.4^d, and later identified as the merger of stars with 1.52 M$\odot$ and 0.16 M$\odot$ (Tylenda et al. 2011).

Instead of increasing mass transfer in a binary system or the internal mixing of a single star due to fast rotation in the presence of a strong magnetic field, the merger hypothesis should describe the nature of V1309 Sco, which states that blue stragglers stars (BSs) spend a long lifetime as low-q stars ($q_{Sco} = m_2/m_1 \approx 0.10$) and result from the merger between two main sequence stars in dynamic interaction. In dense environments, collisions between stars are relatively common, and it has long been believed that BSs is the result of the merger of two old, red stars. Field stars like V1309 Sco are difficult to discover as BSs because the main-sequence turnoff (MSTO) point is not precisely defined in a field colour-magnitude diagram (CMD; Fig. 1). The change in its colour at a relatively high rate, with $\Delta(\mathrm{J}-\mathrm{K_s}) \approx 0.98^m$ in 5 years, demonstrates that the system is getting bluer and hotter with time, mimicking the behaviour of a BSs.

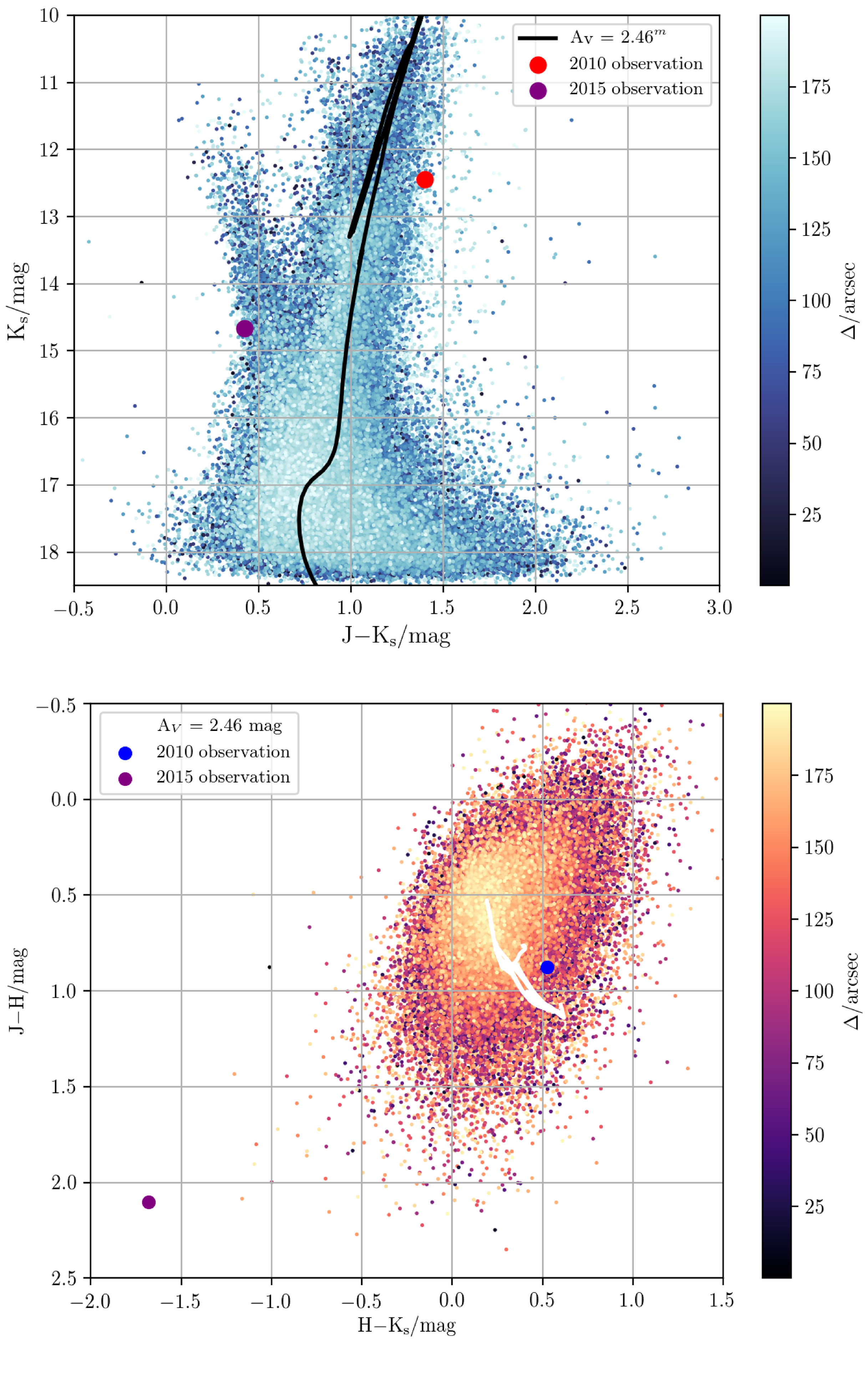

Figure 1: The VVV-PSF J−K$_s$ vs. K$_s$ colour-magnitude diagram (top) and H−K$_s$ vs. J−H colour-colour diagram (bottom) for 357.445 stars located within 15" radius of V1309 Sco region. The red/blue and purple dots in each diagram represents observations in 2010 and 2015, respectively. Isochrones for the bulge population for a stellar age of 10 Myr, solar metallicity (Z = 0.0122), extinction-level A$_V$ = 2.46^m and escalated for the distance of the Galactic centre (d ≈ 8^{kpc}) are also shown as black/white curves.

Main properties of V1309 Sco system: Location in equatorial and Galactic coordinates, extinction towards the region of V1309 Sco, kinematic distance, absolute magnitude in Ks-filter, VVV-DR4 photometry in J, H and Ks filters, orbital period from the Lomb-Scargle implementation, modulation amplitude, significance level based on Baluev's test, mid-phase time, parallax and G-mag from Gaia DR2 project and proper motion measurements from the VIRAC project.

α, δ **(J2000)**	269.38724, −30.71945
$\boldsymbol{l}^\circ$, $\mathbf{b}^\circ$	359.7854, −3.1346
$\mathbf{A}_{Ks}$**/mag**	0.37
$\mathbf{A}_V$**/mag**	2.46
$\mathbf{d}^{kpc}$	2.1
$(\mathbf{K_s}\text{-}\mathbf{abs} \pm \sigma)^m$	2.72 ± 0.2
$(\mathbf{J}_{2010}, \mathbf{J}_{2015})^m$	(13.849, 15.080)
$(\mathbf{H}_{2010}, \mathbf{H}_{2015})^m$	(12.973, 12.978)
$(\mathbf{Ks}_{2010}, \mathbf{Ks}_{2015})^m$	(12.449, 14.659)

$P_{orb} \pm \sigma$**/days**	0.498194 ± 0.000014
Δ**Ks** $\pm\, \sigma^m$	0.030 ± 0.003174
Θ**: Baluev's sign.**	3×10^{-10}
φ_0**/days**	55386.108931
$\bar{\omega}_{Gaia}$	−
$(\mathbf{G} \pm \sigma)^m$	19.27 ± 0.01
$\mu \pm \sigma$**/(mas/yr)**	5.58 ± 2.30
$\mu_{\alpha\cos\delta} \pm \sigma$**/(mas/yr)**	0.91 ± 2.31
$\mu_\delta \pm \sigma$**/(mas/yr)**	5.51 ± 2.30

Near-IR variability data analysis

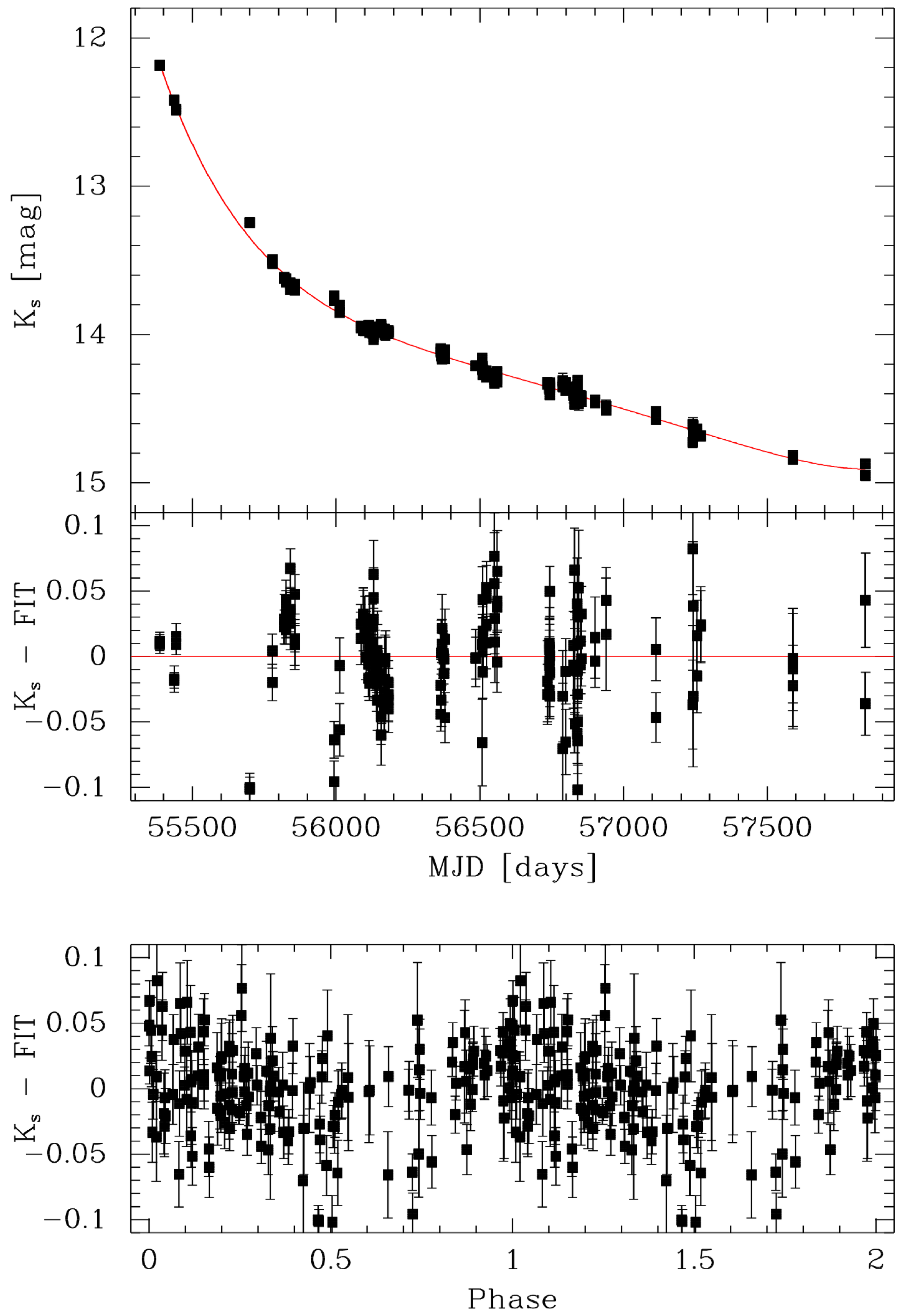

Figure 2: Post-outburst VVV K$_s$-filter light curve and the polynomial fit used to remove the long term variation (red curve) are presented in the top panel. The residual light curve calculated subtracting the original one by the polynomial is presented in the central panel. The phased residual light curve on a period of 0.498^d is presented on the bottom panel, with a modulation amplitude of ΔK$_s$ = 0.030^m.

A periodic signal of P$_0$ ≈ 0.7 days and amplitude modulation of ΔK$_s$ ≈ 0.15^m was presented in the pre-outburst optical data of V1309 Sco. We searched for a periodic counterpart on the post-outburst near-IR light curve from the VVV(X) Surveys through the Lomb-Scargle (LS; Zechmeister & Kurster 2009) method, which provides a straightforward solution based on a Fourier-like power spectrum in order to detect and fit a sine-like periodic component $y(t_k|\omega,\theta) = \Pi_\omega\theta$ at an unevenly-sampled data-set $\Lambda = \{t_k, y_k|\sigma_k\}$, with $t_k \neq t_0 + h\Delta\, t,\ h \in \mathbb{N}$, following VanderPlas & Ivezic 2015:

$$\mathrm{P}_N(\omega) = \frac{(\mathbf{y}^\intercal\mathbf{\Sigma}^{-1}\mathbf{\Pi}_\omega) \times (\mathbf{\Pi}_\omega^\intercal\mathbf{\Sigma}^{-1}\mathbf{\Pi}_\omega) \times (\mathbf{\Pi}_\omega^\intercal\mathbf{\Sigma}^{-1}\mathbf{y})}{\mathbf{y}^\intercal\mathbf{\Sigma}^{-1}\mathbf{y}} \tag{1}$$

$$\mathbf{\Pi}_\omega = \begin{pmatrix} \sin\omega\, t_1 & \cos\omega\, t_1 \\ \sin\omega\, t_2 & \cos\omega\, t_2 \\ \vdots & \vdots \\ \sin\omega\, t_k & \cos\omega\, t_k \end{pmatrix} \qquad \mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{pmatrix} \qquad \mathbf{\Sigma} = \begin{pmatrix} \sigma_1^2 & 0 & \dots & 0 \\ 0 & \sigma_2^2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \sigma_k^2 \end{pmatrix} \tag{2}$$

A frequency grid spanning from two to fifty hours, appropriate to the kind of system studied was chosen, which resulted on an orbital period of P$_{orb}$ = 0.498194±0.00014^d, and a modulation amplitude of ΔK$_s$ = 0.030±0.003^m (Ferreira et al. 2019). Even with a simple false-alarm test based on Baluev (2008) method estimating a great significance of this signal, the resultant period along with the relatively small amplitude must be seen with caution and can be interpreted as no longer the existence of a binary system post-outburst, demonstrating that the results could be related to a BSs. Some of those systems selected in the optical colour-magnitude diagram of NGC 5466 by example, present periodic signals in the range of P = 0.34−0.51^d with amplitudes of ΔV = 0.15−0.33^m. Evidently the orbital period found is in accordance with the values presented in Mateo et al. (1990), however, it is important to note that a different behaviour in the near-IR compared with the optical variability is expected for many classes of eclipsing and pulsating variables.

References

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