

# A low-mass-ratio and deep contact binary as the progenitor of the merger V1309 Sco

Li-Ying Zhu, Er-Gang Zhao and Xiao Zhou

Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; [zhuly@ynao.ac.cn](mailto:zhuly@ynao.ac.cn)  
Key Laboratory of the Structure and Evolution of Celestial Objects, Chinese Academy of Sciences, Kunming 650011,  
China  
University of the Chinese Academy of Sciences, Beijing 100049, China

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**Abstract** Nova Sco 2008 (=V1309 Sco) is an example of a V838 Mon type eruption rather than a typical classical nova. This enigmatic object was recently shown to have resulted from the merger of two stars in a contact binary. It is the first stellar merger that was identified to be undergoing a common envelope transient. To understand the properties of its binary progenitor, the pre-outburst light curves were analyzed by using the W-D method. The photometric solution of the 2002 light curve shows that it is a deep contact binary ( $f = 89.5(\pm 40.5)\%$ ) with a mass ratio of 0.094. The asymmetry of the light curve is explained by the presence of a dark spot on the more massive component. The extremely high fill-out factor suggests that the merging of the contact binary is driven by dynamical mass loss from the outer Lagrange point. However, the analysis of the 2004 light curve indicates that no solutions were obtained even at an extremely low mass ratio of  $q = 0.03$ . This suggests that the common convective envelope of the binary system disappeared and the secondary component spiraled into the envelope of the primary in 2004. Finally, the ejection of the envelope of the primary produced the outburst.

**Key words:** stars: binaries: close — stars: binaries: eclipsing — stars: individuals (V1309 Sco) — stars: evolution — stars: mass-loss

## 1 INTRODUCTION

Contact systems are short-period close binary stars where both components are filling their critical Roche lobes and sharing a common envelope. They are formed from near-contact binaries via mass transfer and/or angular momentum loss (e.g., Qian 2002a,b; Zhu & Qian 2006, 2009; Zhu et al. 2009, 2012). This kind of binary star is oscillating around a critical mass ratio (e.g., Qian 2001a,b, 2003a,b) and will merge into a rapidly rotating single star (e.g., Qian et al. 2005b; Zhu et al. 2005, 2011). Searching for the mergers of contact binaries is a key question in stellar astrophysics.

V1309 Sco was discovered as Nova Sco 2008 on JD 2454712 in September 2008 (Nakano et al. 2008). However, the subsequent evolution showed that it is a new type of outburst rather than a typical classical nova (e.g., Mason et al. 2010). Early spectroscopic data revealed an F-type giant that later evolved to K- and M-types (Mason et al. 2010; Rudy et al. 2008a,b). As pointed out by Tylenda et al. (2011), it exhibits strong characteristics of V838 Mon type eruptions, i.e. evolution to very low effective temperatures after maximum brightness and during the decline (Tylenda & Soker 2006). Some common features of V1309 Sco and V838 Mon type outbursts in general include an outburst amplitude of 7–10 magnitudes, an erup-

tion timescale on the order of months, expansion velocities of a few hundred  $\text{km s}^{-1}$  (instead of a few thousand as in classical novae), and a complete lack of any high-ionization features.

By using archive photometric data collected in the OGLE project during about six years before the outburst, Tylenda et al. (2011) concluded that the progenitor of V1309 Sco was a contact binary with an orbital period of about 1.4 days. The binary system quickly evolved towards its merger and produced the eruption observed in 2008. Nandez et al. (2014) pointed out that the progenitor consists of a  $1.52 M_{\odot}$  giant and a  $0.16 M_{\odot}$  companion with an orbital period of  $\sim 1.4$  days and evolves toward the merger primarily because of Darwin instability. The investigation of Pejcha (2014) indicated that the period decay timescale  $P/\dot{P}$  decreased from  $\sim 1000$  to  $\sim 170$  years in about six years revealing a variable rate of mass loss. McCollum et al. (2014) showed the merger remnant's brightness in optical bandpasses, near-IR bandpasses, and the Spitzer  $3.6 \mu\text{m}$  and  $4.5 \mu\text{m}$  channels has varied by several magnitudes and in complex ways suggesting the occurrence of a dust formation event. The purpose of the present paper is to understand the origin of the outburst by analyzing the light curves of the progenitor of V1309 Sco. Our results indicate that the progenitor of V1309 Sco is a deep con-

tact binary with a low mass ratio that is nearly filling its outer critical Roche lobe and is rapidly undergoing mass and angular momentum loss.

## 2 ANALYSIS OF THE LIGHT CURVES

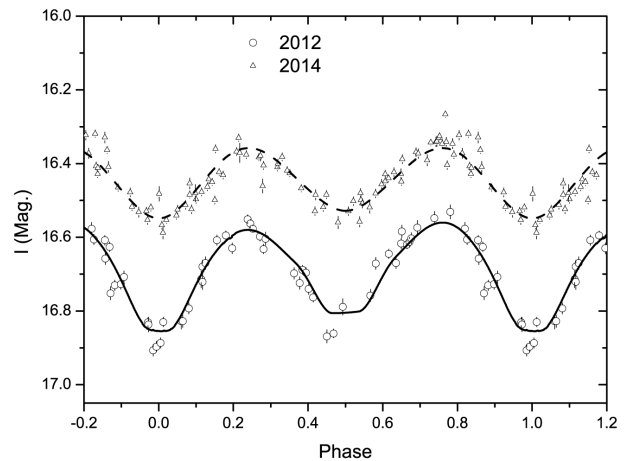
V1309 Sco was included in one of the stellar fields by the OGLE team. Therefore, precise photometric data in  $I$ -band were obtained for six years before the outburst and were presented by Tylenda et al. (2011). Those photometric data obtained in 2002 were analyzed by using the Wilson-Devinney (W-D) method (Wilson & Devinney 1971; Wilson 1994). The corresponding light curve is shown in Figure 1 as open circles. The temperature of the primary (star 1, the hotter component star eclipsed at the primary light minimum) was taken as  $T_1 = 4500$  K (Tylenda et al. 2011). The bolometric albedo  $A_1 = A_2 = 0.5$  and the gravity-darkening coefficients  $g_1 = g_2 = 0.32$  were used because of their convective envelopes. For a detailed treatment of limb darkening, the logarithmic functions for both the bolometric and bandpass limb-darkening laws were used. The bolometric limb-darkening coefficients  $x_{1\text{bolo}}, x_{2\text{bolo}}, y_{1\text{bolo}}$  and  $y_{2\text{bolo}}$ , and the passband-specific limb-darkening coefficients,  $x_{1I}, x_{2I}, y_{1I}$  and  $y_{2I}$  were chosen from van Hamme’s table (van Hamme 1993) and are listed in Table 1. It is found that solutions converged at mode 3 and the adjustable parameters are: the orbital inclination  $i$ ; the mean temperature of star 2,  $T_2$ ; the monochromatic luminosity of star 1,  $L_{1I}$ ; and the dimensionless potential ( $\Omega_1 = \Omega_2$  for mode 3).

The  $q$ -search method was used to determine the mass ratio. We focus on searching for photometric solutions with mass ratio from 0.03 to 1.5, and solutions were obtained for 147 values of the mass ratio. The relation between the resulting sum  $\Sigma$  of weighted square deviations and  $q$  is plotted in Figure 2. It is found that the solution converged at  $q = 0.1$  with the lowest value of  $\Sigma$  indicating that the theoretical light curve based on the solution is the best one to fit the observations. Then,  $q$  was treated as an adjustable parameter and the value of 0.1 was taken as the initial value. Finally, photometric elements were obtained and it is found that the solution converged at  $q = 0.094$ . The corresponding photometric solutions are listed in Table 1.

As shown in Figure 1, the light curve of V1309 Sco in 2002 displayed a negative O’Connell effect, i.e., the light maximum following the primary minimum is lower than the other one. The components of V1309 Sco are cool stars. The deep convective envelope along with rapid rotation can produce a strong magnetic dynamo and solar-like magnetic activity. It is expected that dark spots should be observed on photospheres. In the W-D method, there are four parameters for each spot: spot center longitude ( $\theta$ ), spot center latitude ( $\phi$ ), spot angular radius ( $r$ ), and spot temperature factor ( $T_f$ ), all in units of radians. This is because  $T_f = T_d/T_0$ , where  $T_d$  is the temperature of the spot and  $T_0$  is the local effective temperature of the adjacent photosphere. Our solution suggests that the asymmetry of the light curves can be plausibly explained as the

**Table 1** Photometric Solutions for V1309 Sco

Parameters	Photometric elements	errors
$g_1 = g_2$	0.32	assumed
$A_1 = A_2$	0.5	assumed
$x_{1\text{bolo}} = x_{2\text{bolo}}$	0.313	assumed
$y_{1\text{bolo}} = y_{2\text{bolo}}$	0.660	assumed
$x_{1I} = x_{2I}$	+0.356	assumed
$y_{1I} = y_{2I}$	+0.360	assumed
$T_1$ (K)	4500	assumed
$q$ ( $M_2/M_1$ )	0.094	$\pm 0.002$
$\Omega_1 = \Omega_2$	1.8854	$\pm 0.0249$
$T_2$ (K)	4354	$\pm 161$
$i$	73.4	$\pm 7.0$
$L_1/(L_1 + L_2)$ (I)	0.8929	$\pm 0.0032$
$r_1$ (pole)	0.5546	$\pm 0.0076$
$r_1$ (side)	0.6292	$\pm 0.0133$
$r_1$ (back)	0.6514	$\pm 0.0158$
$r_2$ (pole)	0.2074	$\pm 0.0129$
$r_2$ (side)	0.2189	$\pm 0.0161$
$r_2$ (back)	0.2980	$\pm 0.0990$

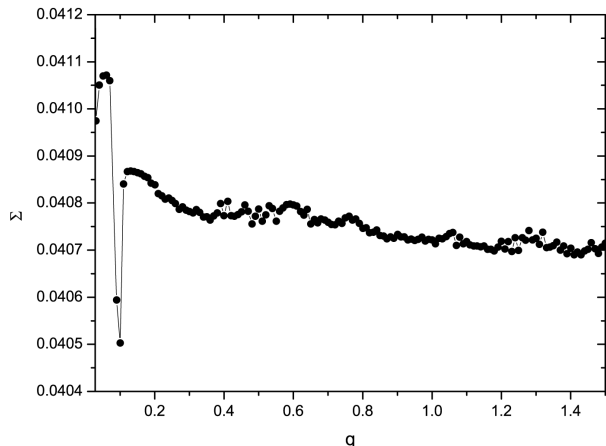
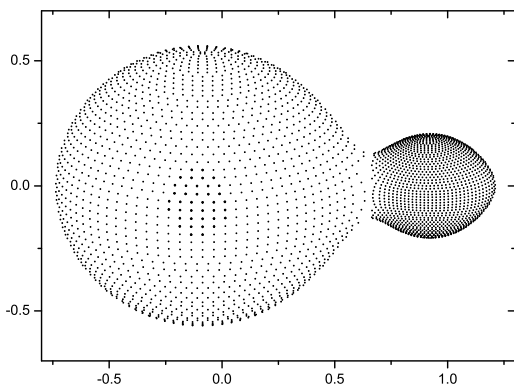


**Fig. 1** Theoretical light curves calculated by using the W-D method. Open circles refer to  $I$ -band data points observed in 2002, while open triangles refer to observations in 2004. The theoretical light curve (the solid line) obtained by using data observed in 2002 reveals that V1309 Sco is a low-mass-ratio and deep contact binary, while the one (the dashed line) for 2004 observations was computed by fixed  $q = 0.03$ .

presence of one dark spot on the more massive component. The parameters of the dark spot are shown in Table 2. The theoretical light curve is plotted in Figure 1 as the solid line that fits the observations well. The corresponding geometric structure at phase 0.25 is displayed in Figure 3. The photometric solution indicates that the temperature of the dark spot is about 350 K lower than that of the stellar photosphere on the more massive component star. The dark spot covers 1.8% of the total photospheric surface which is much larger than that of a spot on the Sun (the area of a sunspot is usually less than 1% of the photospheric surface of the Sun). However, the solution of the dark spot derived with the W-D method is definitely not unique. The spot may be composed of a group of smaller spots.

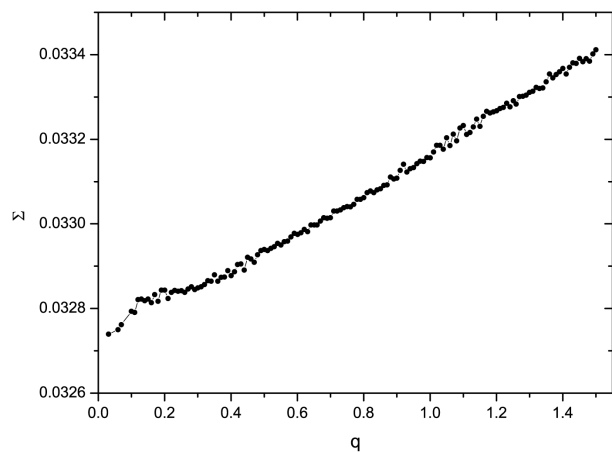
**Table 2** Parameters of the Dark Spot on the More Massive Component.

Spot parameters	Value
$\theta$ (radian)	1.390
$\phi$ (radian)	4.688
$r$ (radian)	0.224
$T_f(T_d/T_0)$	0.923

**Fig. 2** The relation between  $\Sigma$  and  $q$  obtained based on the photometric data in 2002. It is shown that the minimum of  $\Sigma$  is at  $q = 0.1$ .**Fig. 3** Geometrical structure of the progenitor of V1309 Sco at phase 0.25.

### 3 DISCUSSION AND CONCLUSIONS

The photometric solution of the 2002 light curve suggests that V1309 Sco is a contact binary star with an extremely low mass ratio ( $q = M_2/M_1 = 0.094$ ) and an extremely high fill-out factor ( $f = 89.5(\pm 40.5)\%$ ). The asymmetry of the light curve was explained by the presence of a dark stellar spot on the more massive component. The extremely high fill-out factor indicates that the common convective envelope reaches the outer critical Roche lobe and causes a great amount of mass and angular momentum loss. This suggests that the merging of the contact binary is driven

**Fig. 4** The relation between  $\Sigma$  and  $q$  obtained based on the photometric data in 2004. It is shown that  $\Sigma$  is continuously decreasing with the mass ratio  $q$ .

by dynamical mass loss from the outer Lagrange point. This is in agreement with the rapid decay in the orbital period (e.g., Pejcha 2014). The period decay timescale  $P/\dot{P}$  decreased from  $\sim 1000$  to  $\sim 170$  years in about 6 years, which suggests that the dynamical mass-loss rate was increasing.

The binary progenitor of V1309 Sco consists of a giant and a main-sequence companion (e.g., Nandez et al. 2014). The masses of the primary and the secondary were estimated as  $1.52 M_\odot$  and  $0.16 M_\odot$  respectively by Nandez et al. (2014) with a mass ratio of  $\sim 0.105$ . This is consistent with the present value ( $q = 0.094$ ). According to the result obtained by Stępień (2011), the instability resulting in the merging of both components was triggered by a dramatic increase in the moment of inertia of one of the component stars when it approached the base of the red giant branch. However, our photometric solution indicates that the merging produced dynamical mass loss through the  $L_2$  point.

To understand the physical properties of V1309 Sco before merging, we also analyzed the  $I$ -band light curve in 2004 (open triangles). The relation between  $\Sigma$  and  $q$  is shown in Figure 4. As displayed in the figure, the value of  $\Sigma$  is continuously decreasing with the mass ratio  $q$ . This indicates that no reliable solutions can be obtained even at an extremely low mass ratio of  $q = 0.03$ . The theoretical light curve in Figure 1 (the dashed line) was calculated by fixed  $q = 0.03$ . This could be explained as the disappearance of the common convective envelope of the contact binary system suggesting that the main-sequence companion has started to spiral into the envelope of the giant primary and formed a real “common envelope.” This evolutionary process was discussed by Ivanova et al. (2013b,a). The circumstellar material obscured the binary system, which may cause the optical brightness dip before the outburst (see fig. 1 in the paper by Tylenda et al. (2011)).

Some low-mass-ratio and deep contact binary stars were discovered by Qian et al. (2005b, 2011), Yang et al.

(2012, 2013), Samec et al. (2011) and Zhu et al. (2005, 2011) where the fill-out factor ( $f$ ) is higher than 50%. The orbital periods of some targets are continuously decreasing. Some examples are GR Vir (Qian & Yang 2004), FG Hya (Qian & Yang 2005), IK Per (Zhu et al. 2005), CU Tauri and TV Muscae (Qian et al. 2005a), and XY LMi (Qian et al. 2011). As the period is decreasing, the inner and outer critical Roche lobes will be shrinking and thus will cause  $f$  to increase. Finally, they will merge into a single rapidly rotating star and produce an eruption like the one observed for V1309 Sco when the convective surface reached the outer critical Roche lobe. However, the pre-burst contact binary V1309 is different from W UMa-type stars. Those stars have their primaries on the main-sequence stage and stay in contact for a long time, but the primary of V1309 Sco is a giant. Continuous monitoring of those stars is very useful for understanding the merging process of contact binary stars.

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