High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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V1187 Herculis: A Red Novae progenitor, and the most extreme mass ratio binary known

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Abstract. Complete BVR_CI_C light curves of V1187 Her were obtained in May 2017 at the Dark Sky Observatory in North Carolina with the 0.81-m reflector of Appalachian State University. Earlier, spectra were taken at the Dominion Astrophysical Observatory with the 1.8-m telescope. The spectral type was found to be F8 $\pm$ 1 V (6250 K), so the binary is of solar-type. V1187 Her was previously identified as a low amplitude ($V < 0.2$ mag), short period, overcontact eclipsing binary (EW) with a period of 0.310726 d. Strikingly, despite its low amplitude, the early light curves show total eclipses (eclipse duration $\approx$ 31.5 minutes), which is a characteristic of an extreme mass ratio binary. A period study covering 11 years reveals a continuous period decrease $dP/dt = -4.7 \times 10^{-9}$ d yr^{-1}. The multi-band Wilson-Devinney light curve solution gives a fill-out of 79% and a mass ratio of only 0.0440 ± 0.0001. There is a cool spot region on the secondary component, which is 400 K hotter than the primary. The inclination is only 66.85 ± 0.05 despite the system's total eclipses.

Keywords. Stars:binaries: eclipsing, stars: individual: V1187 Her

1. Introduction

Many solar type binaries have been found to undergo continuously decreasing orbital periods, presumably due to magnetic braking. A binary continually undergoing such a process will slowly coalesce over time as it loses angular momentum. This is due to ion winds streaming radially outward on stiff magnetic field lines rotating with the binary. Recently, binaries with decaying periods have been found to undergo a catastrophic merger (a Red Novae, hereafter RN). This leads to the formation of a single, fast rotating, spectroscopically, earlier-type star. As a part of the evolution of the RN progenitor, the binary's mass ratio becomes more extreme and the Roche-lobe fill-out increases. It is believed that there is a limiting mass ratio (Li *et al.* 2016) leading to an instability and the occurrence of the RN. V1187 Her is apparently such a binary, and a progenitor of an RN.

V1187 Her was discovered By ROTSE-1 (see Fig. 1; Akerlof *et al.* 2000) and is listed as an EW type, with a ROTSE-1 mag of 11.740 ± 0.008, a period of 0.31076 ± 0.00005 d, and an amplitude 0.205 mag. The binary was described in Blaettler & Diethelm (2007), along with a finding chart (Fig. 2) and an ephemeris:

$$\mathrm{HJD(MinI)} = 2453877.4694 + 0.310726 \times E. \tag{1.1}$$

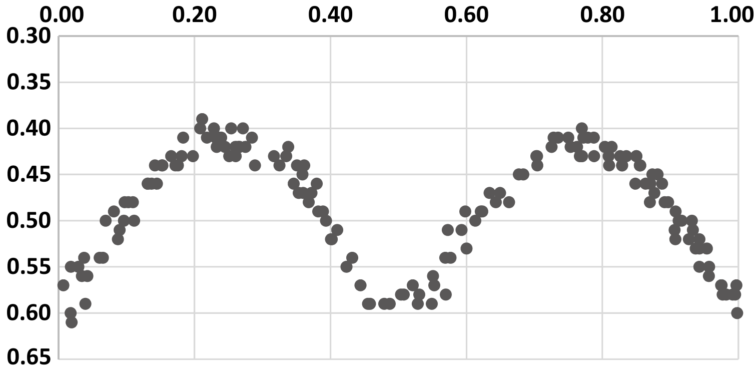

Figure 1. ROTSE-1 light curve of V1187 Her.

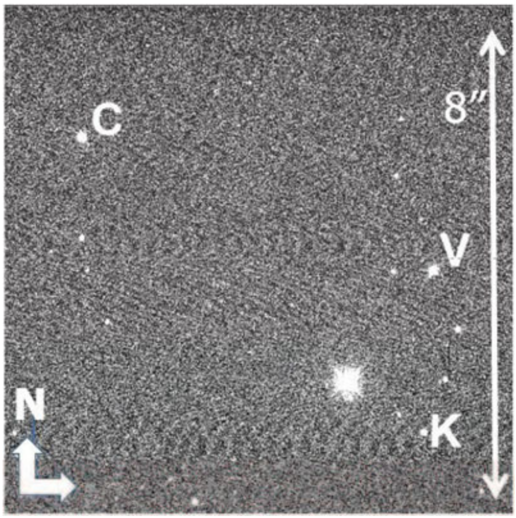

Figure 2. V1187 Her finding chart.

Eight times of minimum light from ROTSE-I observations were given in Diethelm (2007). The system also appeared in the 80th Name-List of Variable Stars (Kazarovets *et al.* 2013). Two timings of minimum light are given in Diethelm (2010a).

V1187 Her was observed as part of a student/professional collaborative study of interacting binaries program with data obtained through SARA South observations. The $BVRI$ light curves were taken with the Dark Sky Observatory (DSO) 0.81-m reflector at Philips Gap, North Carolina, on 20 and 27 May, 2017. The telescope has a thermoelectrically cooled ($-40\,^{\circ}$C) 2K $\times$ 2K Apogee Alta CCD chip. The observers were D. Caton, R. Samec, D. Faulkner, B. Hill, and D. Gentry.

On May 20, 2017, we obtained 93 observations in B, 147 in V, 156 in R_C, and 158 in I_C. The nightly C-K values stayed constant throughout the observing run with a precision of better than 1%. Exposure times were 150 s in B, 30 s in V and 20 s in R_C and I_C. The R_C and I_C light curves of May 20, 2017 are shown in Fig. 3. The May 27 observations included185 in B, 187 in V, 162 in R_C and 187 in I_C. The nightly C-K values stayed constant throughout the observing run with a precision of 1%. Exposure times varied from 250 to 275 s in B, 80 to 90 s in V and 30 to 50 s in R_C and I_C.

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Table 1. New eclipse timings

Timing (HJD)	Type
2457893.94583 ± 0.0007	I
2457900.7845 ± 0.00106	I
2457893.79034 ± 0.00035	II
2457900.62773 ± 0.00105	II

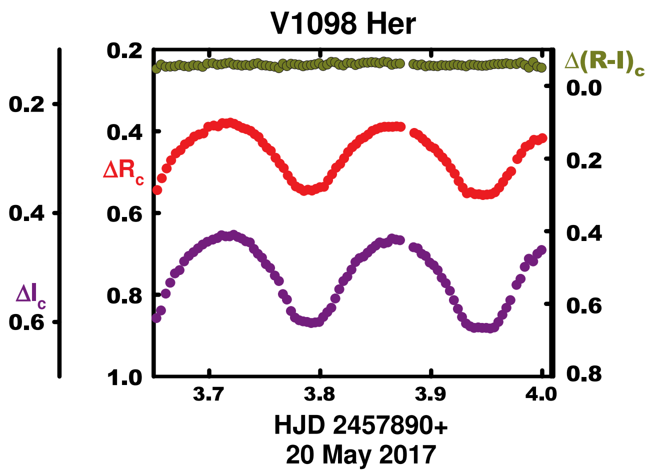

Figure 3. The May 20, 2017 R_C and I_C light curves.

2. Targets

The variable, indicated by the letter V in Fig. 2, is V1187 Her. Alternative names are GSC 2587 1888, NSVS 7913634, ROTSE1 J162919.83+353959.2 [$\alpha(2000)$ = 16h 29m 19.890s, $\delta(2000) = 35° 40' 2.90''$ ICRS], $J-K = 0.341$, F8V (2MASS), TYC 2587 1888, V=15.10, $B-V = 0.489 \pm 0.134$.

The comparison star C is GSC 2587 0918, [$\alpha(2000)$ = 16h 28m 48.2441s, $\delta(2000) = 35° 42' 29.300''$], 3UC252-115600, $B-V = 0.489$; $J-K = 0.44$ (2MASS), G7V, $V = 11.16$. The check star K is GSC 2587 0684, [$\alpha(2000)$ = 16h 29m 19.0219s, $\delta(2000) = 35° 37' 5.340''$], 3UC252-115633, $V = 13.84$, $J-K = 0.36$, G0V, (2MASS).

3. Period Study

Four times of minimum light were calculated from our present observations, two primary and two secondary eclipse timings. They are listed in Table 1. The following linear and quadratic ephemerides were determined from all available times of minimum light:

$$\mathrm{HJD(MinI)} = 2457893.9484 \pm 0.0019 + 0.31076465 \pm 0.00000019 \times E, \tag{3.1}$$

and

$$\begin{aligned}\mathrm{HJD(MinI)} \;\; = \;\; & 2457893.94565 \pm 0.0016 + 0.31076278 \pm 0.00000050 \times E \\ & +1.42 \pm 0.36 \times E^2.\end{aligned} \tag{3.2}$$

The O-C study covers some 11 years and about 13,000 orbits (Fig. 4). The period is decreasing as one might expect for magnetic breaking. According to the light curve solution the more massive component has a mass of 22.7 times that of the less massive one. Equation 3.2 yields a dP/dt of 2.3×10^{-7} d yr^{-1}, which corresponds to a mass flow rate $dM_2/dt = -8.9 \times 10^{-9}\ M_{\odot}$ d^{-1}, assuming a main sequence mass value for the primary component. It is thought that the more massive component steadily absorbs the secondary during normal evolution, so this period change follows the expected course.

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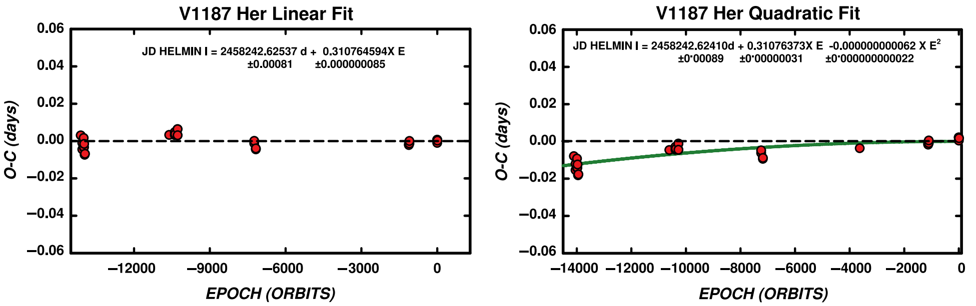

Figure 4. *Left*: $O-C$ residuals for the linear ephemeris (Eqn. 3.1). *Right*: $O-C$ residuals for the quadratic ephemeris (Eqn. 3.2).

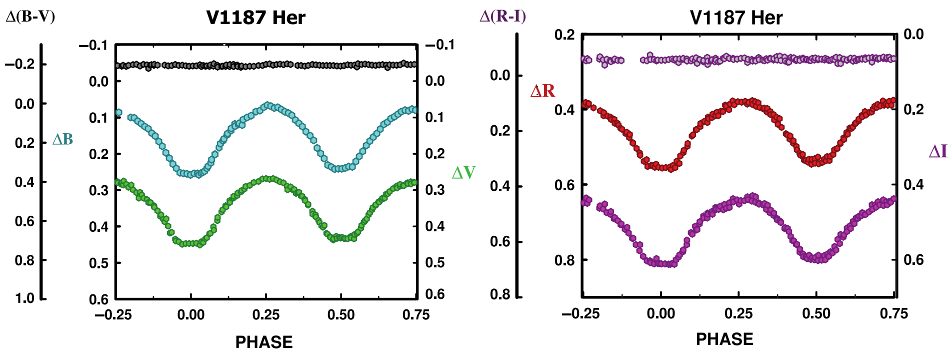

Figure 5. V1187 Her observed light curves.

The minimum mass ratio of W UMa binaries is thought to be $q = 0.071$ to 0.078. Since the mass ratio of V1187 Her is 0.044, far smaller than this value, the binary is very close to coalescing.

4. Light Curve Solution

The amplitudes of the light curves are only ≈ 0.17-0.19 mag in all bands, which is very small considering the eclipses are total (Fig. 5). The O'Connell effect (difference in the maxima), classically thought of as an indicator of spot activity, is only 0.003 to 0.11 mag in all bands, and a minor spot is needed to solve the light curves. The minima show a difference of ≈ 0.015 mag in all curves, indicating that the temperature difference between the components does exist despite the tiny amplitudes. The B ,V, R_C and I_C curves were carefully pre-modeled with Binary Maker 3.0 (Bradstreet & Steelman 2002) fits in all bands. The parameters were then averaged and input into a 4-color simultaneous light curve solution using the Wilson-Devinney program (Wilson & Devinney 1971; Wilson 1990). The solution (Fig. 6) was computed in Mode 3, the over-contact mode. Convective parameters $g = 0.32$, $A = 0.5$ were used. Since the eclipses were total, no q-search was performed. Due to the shallow curves one important element is the possibility of third light. So third light was a part of the elements iterated throughout the process. It remained viable throughout the calculation. A second, non-third light solution was calculated showing a smaller residual.

5. Discussion

V1187 Her is found to be a short period, extreme mass ratio W UMa eclipsing binary. For the third light solution, it was found to make up only ≈ 0.36% relative light in all filters. The primary component emits ≈ 92% of the total system light in the final solution.

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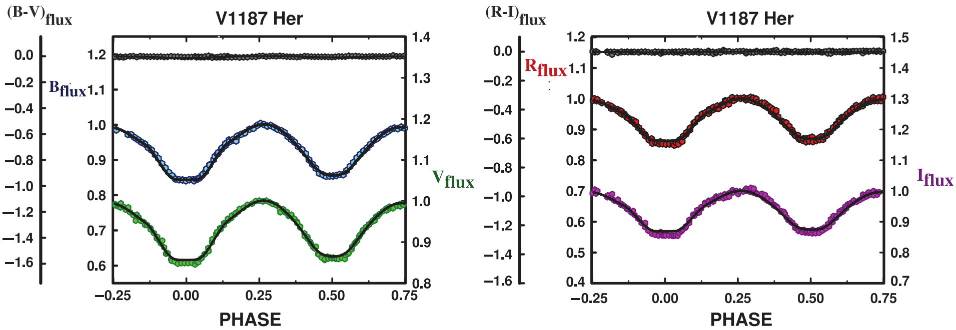

Figure 6. V1187 Her observed and computed light curves.

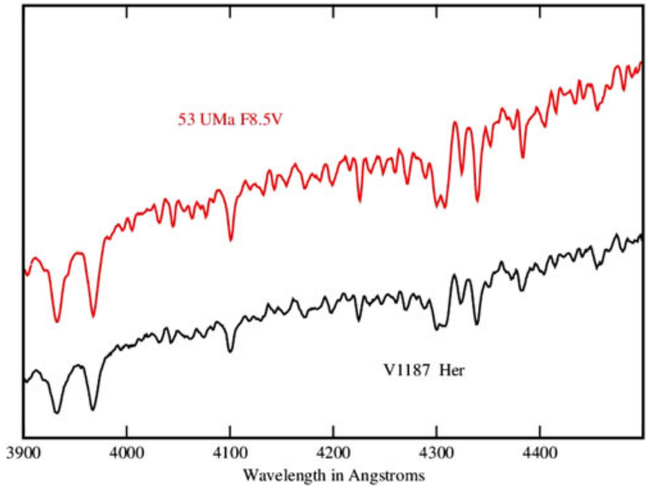

Figure 7. V1187 Her DAO spectra.

So the 0.044 mass ratio determination and the inclination (66.85 ± 0.05) is the main cause of the very shallow amplitude (< 0.2 mag). Strengthening this determination is the total eclipse which would occur at a minimum inclination of $\approx 63°$. Recently, a paper featuring a R and V light curve analysis and Hα line study of ASAS J083241+2332.4 found its mass ratio to be ≈ 0.06 (Sriram *et al.* 2016). Such extremely low mass ratio binary systems are rare and only three systems have been reported so far with mass ratios under ≈ 0.075: V53 ($q = 0.060$; Kaluzny *et al.* 2013), V857 Her ($q = 0.065$; Qian *et al.* 2005), and SX Crv ($q = 0.072$; Zola *et al.* 2004). V1187 Her is probably the most extreme of this rare class.

6. Conclusion

V1187 Her has the most extreme mass ratio of the solar type binaries. The 11 year orbital study (12,000 orbits) reveals an negative quadratic ephemeris. This decrease may be due to magnetic braking as a plasma wind is discharged along stiff rotating magnetic field lines. DAO spectra yields a F8.5V spectral type (Fig. 7). The Wilson-Devinney program solution gives a mass ratio of 0.043983 ± 0.00008 and the Roche lobe fill-out is also extreme, about 79% for this over-contact binary. Its component temperature difference is ≈ 38 K. The extreme mass ratio condition (despite its 68° inclination) allows an eclipse duration of ≈ 31.5 minutes. Despite its deep contact state, this W UMa binary is of W-type (the less massive component is hotter). Its magnetic character is attested by the cool spot modeled on its primary component. Radial velocity curves would allow determination of the binary's absolute elements.

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