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PG 1413+01: A WHITE DWARF–RED DWARF ECLIPSING BINARY

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ABSTRACT

The star PG 1413+01, discovered in a survey for blue stars at high galactic latitude, is an eclipsing binary with a period of 8^h16^m. The system resembles the red dwarf–white dwarf binary BD +16°516. The primary is a hot white dwarf with a mass of $\sim 0.7 \pm 0.3\ M_\odot$. The faint secondary has been detected in the red and is probably a dwarf of spectral type M3 ± 3. The two components are separated by around 2 $R_\odot$. Since it is unlikely that the hot white dwarf is heated by accretion, the binary system has probably been in its present state for less than 10^6 years. It is possible that the system is a post–common-envelope binary.

Subject headings: stars: eclipsing binaries — stars: late-type — stars: white dwarfs

I. INTRODUCTION

PG 1413+01 was found in a survey for blue stellar objects at high galactic latitude (Green 1976). Its unusual nature was noted while a spectrum was being taken on 1975 March 14: as observed on the integrating television guiding system of the 5 m Hale telescope it faded rapidly below the detection limit of the system, then reappeared after some 13 minutes. Subsequent photometric, spectrophotometric, and infrared measurements established that PG 1413+01 is an eclipsing binary with a period of about 8^h16^m. The primary is a very hot white dwarf and the secondary an M-type dwarf. The system is reminiscent of BD +16°516 (Nelson and Young 1970; Young and Nelson 1972) and may be representative of a class of binaries which contain a white dwarf and a late-type main-sequence star at small separation.

A finding chart for the object is given in Figure 1. Its position is $\alpha = 14^h13^m03^s.6$, $\delta = +1°31'13''$ (1950), corresponding to a galactic latitude of +58°. Photometric and spectrophotometric observations are presented in § II, eclipse timings and geometric properties in § III, an analysis of the physical characteristics in § IV, and a discussion of evolutionary aspects of § V.

II. SPECTRA AND PHOTOMETRY

A low-dispersion spectrum obtained with the Cassegrain image-tube spectrograph at the 5 m Hale telescope shows very broad and shallow Balmer lines in absorption, characteristic of hot white dwarfs. The existence of these lines has been confirmed on a spectrum obtained with a SIT vidicon camera. The lines are so broad and weak that it would be very difficult to obtain a radial-velocity curve.

Observations out of eclipse obtained with the multichannel spectrometer at a resolution of 160 Å in the blue and 360 Å in the red are shown in Figure 2, together with an observation at 1.65 μm by Willner, Neugebauer, and Becklin. In the blue the flux rises steeply with frequency as $\nu^{1.7}$, nearly consistent with a Rayleigh-Jeans law. The spectrum is well represented in the blue by Shipman's (1971) 50,000 K white-dwarf models, although an infinite temperature blackbody is not ruled out. Broad-band photometry with the Palomar 1.5 m telescope yields $V = 17.01$, $B - V = -0.34$, and $U - B = -1.14$, consistent with the multichannel data.

Initial attempts to detect the system during eclipse were not successful. A photograph obtained with a red-sensitive image tube at the prime focus of the 5 m telescope by Dr. J. E. Gunn did not show the object. Broad-band photometry at the Mount Wilson 2.5 m and the Palomar 1.5 m telescopes did not lead to definite detection of the binary during eclipse.

Multichannel spectrophotometry fully covering two eclipses was obtained with the 5 m telescope on 1975 May 11 and 12. Observations were made at intervals of 13.8 s, each observation consisting of a 12.0 s integration in each of the 32 channels through two focal-plane apertures (for a description of the multichannel spectrometer, see Oke 1969). The first night the object was placed in one aperture and the second night in the other one. In order to make corrections for dark counts and for the ratio in gain through the two apertures, observations of empty patches of sky and of the dark count were made each night before and after the eclipse.

A total of 46 and 47 12 s integrations, respectively, were within the period of total eclipse during the two nights. Table 1 gives count rates for groups of channels in the wavelength ranges indicated for both nights together, since there were no significant differences. All standard deviations were derived from the total counts through both focal-plane apertures, most of which are contributed by the sky. The total count rate in eclipse at all wavelengths is $8.6 \pm 2.3\ \mathrm{s}^{-1}$; for wavelengths longer than 4900 Å it is $9.2 \pm 2.2\ \mathrm{s}^{-1}$, significant at the 4 σ level. The total number of counts statistically attributable to the secondary during the two eclipses is about 5000.

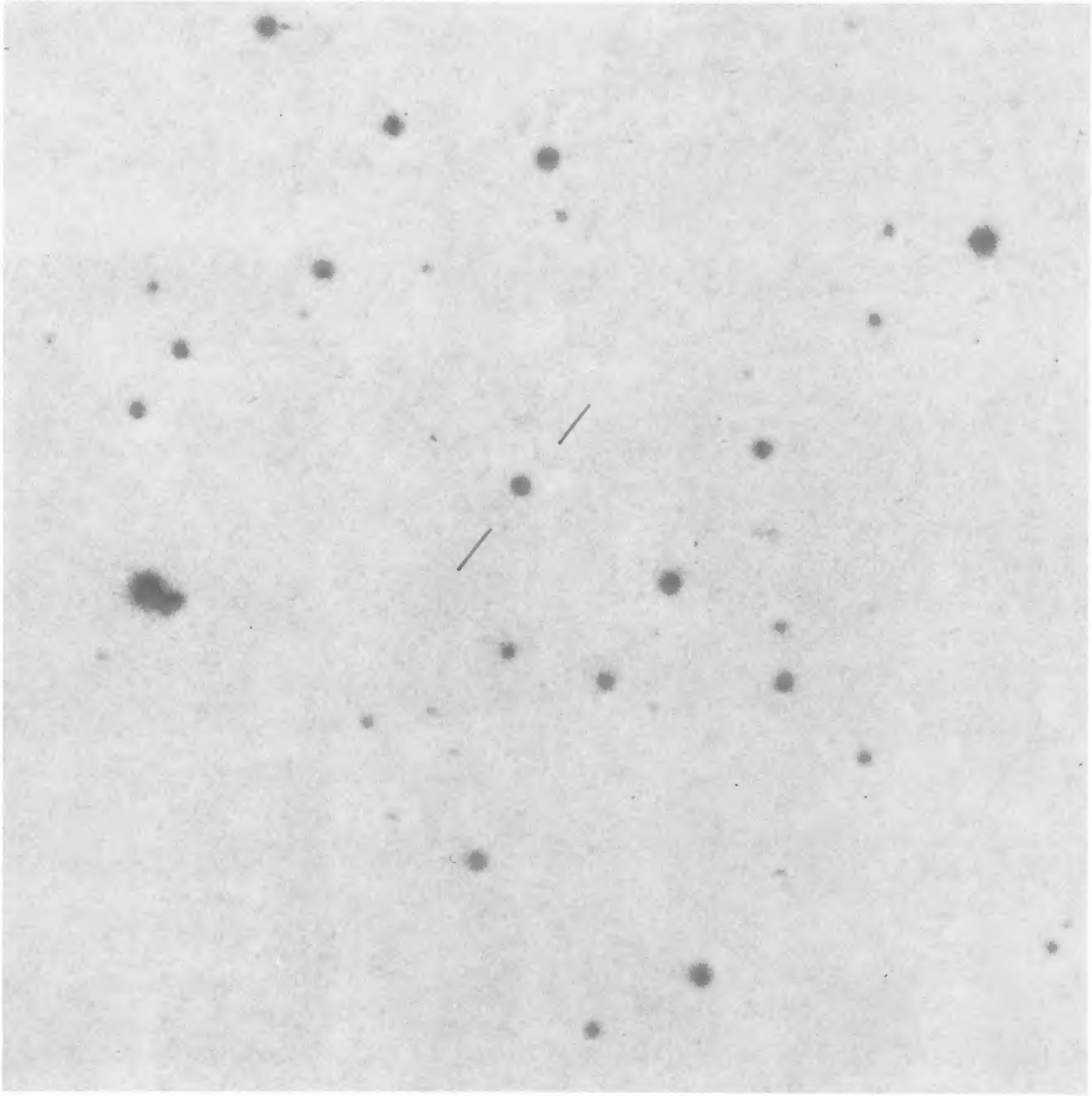

FIG. 1.—Finding chart for the eclipsing binary PG 1413+01. Each side is 7′.6; northeast is at the upper left.

TABLE 1

Spectrophotometric Results of the Binary in Eclipse

Wavelength Range (Å)	Count Rate (s^{-1})	$\log f_\nu$ (ergs cm^{-2} s^{-1} Hz^{-1})
3100–4740...	-0.69 ± 0.80	...
4900–5860....	$+1.05 \pm 1.21$	-28.47
5860–7040....	$+2.84 \pm 0.97$	-27.68
7040–8120....	$+4.20 \pm 1.21$	-27.40
8120–9200....	$+0.76 \pm 0.42$	-27.15
9200–11000...	$+0.40 \pm 0.89$	-27.39

The count rates in each of the wavelength ranges of Table 1 were converted to flux densities. These are plotted in Figure 2 together with the observations out of eclipse. Also shown is infrared photometry obtained by Willner, Neugebauer, and Becklin during eclipses on 1975 June 30 and July 1.

We have compared the energy distribution of the secondary with that of several M-type dwarfs kindly made available by Dr. J. L. Greenstein, and we have consulted visual and infrared photometry of M-type dwarfs given by Veeder (1974). We conclude that its spectral type is M0–M6, where the large range reflects the uncertainties in the photometry of the secondary component. The corresponding range of absolute magnitude M_R is about 7.5–11.5, and the distance modulus $m - M = 13 - 9$, hence M_v (white dwarf) = 4–8, making it one of the most luminous known white dwarfs.

III. LIGHT CURVE AND GEOMETRIC PROPERTIES

As described in the preceding section, the eclipses of 1975 May 11 and 12 were particularly well observed with the multichannel spectrometer at the 5 m telescope. Since these observations yielded no significant detection of the binary in eclipse at wavelengths below 5700 Å, we may assume that the secondary is dark at these wavelengths.

Figure 3 shows observed values of the brightness of the binary, expressed as a fraction of the out-of-eclipse brightness, during ingress and egress on both nights. Each point plotted represents counts in all channels with wavelengths below 5700 Å, integrated over 12.0 s at 13.8 s intervals.

We shall use these observations to derive the relationship between R_w, the radius of the white-dwarf primary; R_m, the radius of the main-sequence secondary; and v, the relative orbital velocity. If the projected separation between the centers of the two stars is $R_m + xR_w$, then ingress and egress are characterized by $-1 < x < 1$. The fraction f_{occ} of the area of the white-dwarf disk occulted by the secondary can easily be derived as a function of x. Since R_m is much larger than R_w, it is feasible to use the approximation

$$f_{\text{occ}}(x) = \frac{1}{\pi}\left[\cos^{-1} x - x(1 - x^2)^{1/2} - \tfrac{1}{3}(1 - x^2)^{3/2}\frac{R_w}{R_m}\right], \tag{1}$$

in which the first two terms correspond to a straight edge. This formula is in error by at most 0.0003 for the minimum value $R_m/R_w = 9.5$, to be derived below.

If the inclination i of the orbit is 90°, then x is a linear function of time t. This is still approximately the case during ingress and egress ($-1 < x < 1$) if $i \neq 90°$, since R_m/R_w is large. Let pR_m be the minimum projected distance of the centers of the stellar disks. Then

$$\begin{aligned} x &= R_w^{-1}[v(t_0 - t)(1 - p^2)^{1/2} \\ &\qquad - R_m(1 - p^2)] \text{ during ingress}, \\ x &= R_w^{-1}[v(t - t_0)(1 - p^2)^{1/2} \\ &\qquad - R_m(1 - p^2)] \text{ during egress}, \end{aligned} \tag{2}$$

where t_0 is the time of mid-eclipse. In practice, we derive x for each photometric observation during ingress and egress from equation (1) by using an estimated value of R_w/R_m. These x values are plotted versus t and least-squares determinations made of t_i, t_e, and β, where

$$\begin{aligned} x &= \beta(t_i - t) \text{ during ingress}, \\ x &= \beta(t - t_e) \text{ during egress}, \end{aligned} \tag{3}$$

where t_i and t_e are epochs of mid-ingress ($x = 0$) and mid-egress ($x = 0$), respectively. From equations (2) and (3),

$$R_w/v = \beta^{-1}(1 - p^2)^{1/2}, \tag{4}$$

$$R_m/R_w = \tfrac{1}{2}\beta(t_e - t_1)(1 - p^2)^{-1}, \tag{5}$$

$$t_0 = (t_i + t_e)/2. \tag{6}$$

The parameter β^{-1} is half the time interval between first external contact and first internal contact of the stellar disks (i.e., half the time covered by the descending or ascending branch of the light curve). Its value from the least-squares solutions was found to be 43.0 and 43.6 s from ingress and egress, respectively, during the first night, and 40.6 and 41.0 s for the second night. We adopt $\beta^{-1} = 42$ s, so

$$R_w/v = 42(1 - p^2)^{1/2}. \tag{7}$$

The least-squares solutions yielded $t_e - t_i = 800.8$ and 800.2 s for the first and second night, respectively. We adopt $\tfrac{1}{2}\beta(t_e - t_i) = 9.5$, so

$$R_m/R_w = 9.5(1 - p^2)^{-1}. \tag{8}$$

Test calculations show that for such a large value of R_m/R_w the errors introduced by the approximation in equation (2) are negligible. We shall use equations (7) and (8) in § IV to derive the properties of the binary system.

Photometric observations covering eclipses are available for eight nights in 1975–1977; see Table 2. These were obtained at the Palomar 5 m and 1.5 m

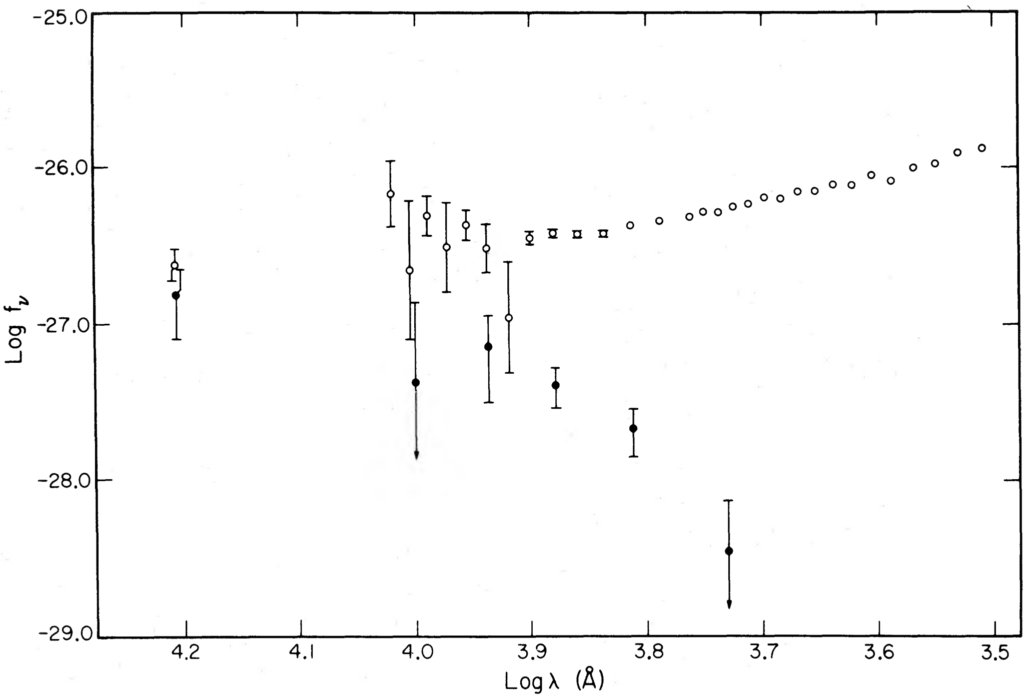

FIG. 2.—Flux $f(\nu)$, in units of ergs $\mathrm{cm^{-2}\,s^{-1}\,Hz^{-1}}$, for the eclipsing binary PG 1413+01. Open circles refer to measurements outside eclipse; filled circles to those during full eclipse when the white dwarf is fully eclipsed by the red dwarf.

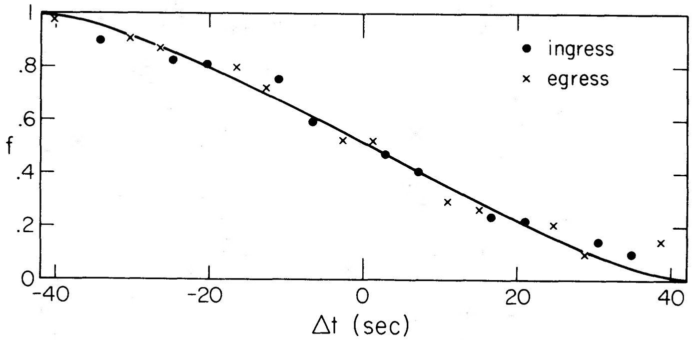

FIG. 3.—Brightness of the binary, expressed as a fraction f of the out-of-eclipse brightness during ingress and egress. The abscissa is defined as $\Delta t = t - t_i$ for ingress and $\Delta t = t_e - t$ for egress, where t_i and t_e are defined in eq. (3). The solid line corresponds to $f = 1 - f_{\mathrm{occ}}$ where f_{occ} is given by eq. (1) for $R_m/R_w = 9.5$.

TABLE 2

BARYCENTRIC JULIAN DATES OF MID-ECLIPSE

Date (UT)	E (cycles)	Observed JD (2,440,000+)	Estimated Uncertainty (s)	Obs. − Pred. (s)
1975 Apr 18........	−67	2520.76693	±1	−5
1975 Apr 30........	−32	2532.81852	±2	−4
1975 May 1.........	−29	2533.85150	±8	−5
1975 May 11........	0	2543.83715	±1	0
1975 May 12........	+3	2544.87014	±1	0
1976 Feb 28........	+851	2836.86259	±5	−7
1977 Mar 18........	+1966	3220.79146	±10	−5
1977 May 14........	+2132	3277.95045	±5	+2
1978 Feb 1.........	+2896	3541.01915	±10	−2

telescopes and the Mount Wilson 2.5 m telescope, with the multichannel spectrometer, broad-band photometry, or SIT vidicon spectrometry. The photometric observations during ingress or egress were used to derive the time corresponding to $x = 0$ (t_i and t_e, respectively), through equations (1) and (2). Mid-eclipse epoch t_0 was derived from equation (6). If only ingress or egress was observed, t_0 was obtained by adding 400.2 s to t_i, or by subtracting 400.2 s from t_e. The values of t_0 given in Table 2 are reduced to the barycenter of the solar system.

The observed mid-eclipse epochs are well represented by

$$\text{JD (mid-eclipse)} = 2442543.837148 + 0.344330809\,E\,. \tag{9}$$

This relation was derived by fitting the average of the two 1975 May epochs and a weighted average of the two 1977 epochs. A visual observation on 1978 February 1 fits well to equation (9), as shown in Table 2.

IV. PHYSICAL CHARACTERISTICS OF THE SYSTEM

We can derive the physical characteristics of the system by using the mass-radius relations for white dwarfs (Hamada and Salpeter 1961) and for low-mass main-sequence stars (Hoxie 1973). Considering the uncertainties as discussed by Hoxie, we decided to adopt a simple $M/M_\odot = R/R_\odot$ relation for the lower main sequence. We assume that the relative orbit of the two stars is circular with radius a. Then

$$p = (a \cos i)/R_m\,, \tag{10}$$

$$v = (GM/a)^{1/2}\,, \tag{11}$$

$$P = (4\pi^2 a^3/GM)^{1/2}\,, \tag{12}$$

where P is the period, and $M = M_m + M_w$.

The solution is carried out as follows. For a given value of p, start with an estimated value of total mass M. Then determine successively a, v, R_w, R_m, i, M_w, and M_m from equations (12), (11), (7), (8), (10), and the mass-radius relations, respectively. The process is iterated until the input value of M equals the sum of the derived M_w and M_m. The final values are well defined within the framework of the assumptions, since the mass of white dwarfs decreases with radius, while it increases for main-sequence stars.[1]

Table 3 exhibits the results. The spectral type of the secondary ranges from about M6 for the $p = 0$ solution to M1 for $p = 0.90$ and about K7 for $p = 0.95$. Hence all solutions with $0 < p < 0.93$ are in accordance with the spectrophotometry in eclipse described in § II which suggested a spectral type in the range M0–M6. The corresponding separation of the binary is 2.4–1.7 $R_\odot$ and the mass of the white dwarf 1.0–0.4 $M_\odot$.

V. EVOLUTION OF THE SYSTEM

The past evolution of this system is of considerable interest, since the white-dwarf progenitor probably developed an envelope of at least $10^2\ R_\odot$ during its red-giant phase. If the binary had its present separation at that time, the interaction between the stars must have been dramatic. It is more likely that the binary separation was much larger at that time and that the orbit of the secondary decayed to its present separation due to dynamical friction and ram pressure drag. Whatever the initial orbital separation, the progenitor of this system, as of BD +16°516 (Young and Nelson 1972) and the cataclysmic variables (e.g., Robinson 1976) was probably a common-envelope binary of the sort discussed by Paczyński (1976).

The very high temperature of PG 1413+01 indicates a high bolometric luminosity of at least 10^{35} ergs s^{-1}. This luminosity may be provided in part by accretion of material lost from its companion. If contraction of the white dwarf due to its increase in mass is neglected, the gravitational energy released by the accreted material is

$$\frac{dE}{dt} = GM_w \dot{M}_w R_w^{-1}\,. \tag{13}$$

For a white dwarf of mass 0.6 $M_\odot$ an accretion rate of at least $10^{-9}\ M_\odot\ \text{year}^{-1}$ is required to produce the observed luminosity. Since the secondary is well outside its Roche limit, the mass flow must be provided by a wind. A mass-loss rate as great as that needed to

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[1] Application of this method to the case of BD +16°516 yields results that are in satisfactory agreement with those obtained by Young and Nelson (1972) who had available both light and radial-velocity curves.

TABLE 3

RADII AND MASSES FOR DIFFERENT VALUES OF THE ORBITAL INCLINATION

p	i	a ($R_\odot$)	R_w ($R_\odot$)	R_m ($R_\odot$)	M_w ($M_\odot$)	M_m ($M_\odot$)
0...........	90°	1.70	0.0151	0.14	0.42	0.14
0.50........	87°.2	1.81	0.0139	0.18	0.50	0.18
0.75........	84°.5	2.00	0.0117	0.26	0.66	0.26
0.90........	80°.0	2.28	0.0088	0.44	0.91	0.44
0.95........	75°.2	2.49	0.0069	0.67	1.08	0.67

provide the white-dwarf luminosity would exhaust the M dwarf in less than 10^9 years. It also seems highly unlikely that the heating by the white dwarf (at $\sim$50,000 K) can affect the wind from the M dwarf, since its surface escape velocity corresponds to about 10^7 K.[2] At a more modest accretion rate the accretion luminosity is insufficient, and the extra luminosity from hydrogen burning is only provided for very short time scales on a recurrent basis (see Paczyński and Zytkow 1978).

Since it seems most unlikely that the white dwarf is heated as a result of interaction with its companion, it is probably young. Estimates of the cooling time for a white dwarf of this large a luminosity, including neutrino cooling and a proper account of the thermal energy reservoir in the ions and partially degenerate electrons, are available only for 1 $M_\odot$ ^{12}C stars (Lamb and Van Horn 1975), for which the time scale is about 10^6 years. It is probable that this object represents a fairly common type of binary system during a very short-lived phase.

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[2] We thank S. P. Hatchett for pointing this out to us.

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