THE ASTROPHYSICAL JOURNAL, 175:L79–L83, 1972 July 15

ULTRASHORT-PERIOD BINARIES. II. HZ 29 (=AM CVn): A DOUBLE-WHITE-DWARF SEMIDETACHED POSTCATACLYSMIC NOVA?*†

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Received 1972 May 10

ABSTRACT

The peculiar white dwarf HZ 29 is in fact an eclipsing binary system with $P \sim 1051^{\mathrm{s}}.05$ ($\sim 17^{\mathrm{m}}.5$). A hydrogen-containing secondary is most unlikely. A satisfactory model has a degenerate helium secondary of mass $\sim 0.041\ M_{\odot}$. We suggest this is the remnant core of a nova secondary which has suffered complete envelope mass loss as a result of gravitational radiation angular momentum losses. The separation of components is $\sim 10^{10}$ cm, primary orbital velocities appear to be marginally detectable, and the period should be increasing by 1 or 2 parts in 10^8 per annum.

I. INTRODUCTION

The peculiar blue object HZ 29 has had a remarkably checkered career in the astronomical literature. Noted by Malmquist (1936) and Humason and Zwicky (1947), its spectral peculiarities were first investigated by Greenstein and Matthews (1957). The latter classified it as a DBp white dwarf (strong He I absorption lines, no detectable hydrogen lines). The helium lines are very shallow and possibly double, and exhibit abnormal relative strengths. Burbidge, Burbidge, and Hoyle (1967) suggested from certain wavelength coincidences that HZ 29 might be a quasi-stellar object; but Wampler (1967), studying photoelectric scans, concluded that it was a hot star, with a continuum distribution similar to that of a blackbody with $T_c \sim 2 \times 10^4$ ° K.

Smak (1967) discovered variability at a very low level (~0.02 mag in this fourteenth magnitude object). The double-humped nature of the light curve with period ~17.5 minutes was confirmed by Ostriker and Hesser (1968). Smak considered that the periodicity indicated a binary system, although a number of spectra taken at short intervals by Greenstein and Matthews did not appear to show any radial-velocity variations. Ostriker and Hesser objected to the binary hypothesis on the grounds that white dwarfs of very low mass would be needed to give a period as long as $\sim 10^3$ seconds while still permitting the close passages indicated by the continuously varying light curve.

More recently, Krzemiński (1972) has reported that slightly different periods are required to fit two stretches of 1967 data, and that minima are redder in $B - V$ but bluer in $U - B$. These color variations are similar to those in the short-period variable WZ Sge (Krzemiński and Smak 1971).

Warner and Robinson (1972) have now made high-speed photometric observations of HZ 29 which leave no doubt that one is observing an eclipsing system. The slight phase

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* *Contributions from the Lick Observatory*, No. 367.

† Work supported in part by the National Science Foundation, through grants GP-22956 and GP-25901.

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jitter observed, the occasional absence of one eclipse, and the color variations suggest a system similar in many respects to the mass-transfer, "hot-spot" model of dwarf novae (Smak 1971; Warner and Nather 1971). Indeed, Warner and Robinson have suggested that HZ 29, or AM CVn as it will now be known to variable star observers, is an extreme member of the class.

The observational material is being published elsewhere (Warner and Robinson 1972); in the following, we wish to concentrate on the theoretical implications of the new observations.

II. THEORETICAL CONSIDERATIONS

The general model of dwarf novae is illustrated in figure 1. According to Faulkner (1971), the evolution of these systems is dominated by the emission of gravitational radiation which, by removing angular momentum, induces changes in the separation of the components and thereby controls mass transfer. In the standard model (Faulkner 1971), given by a simple power-law approximation to the essentially main-sequence secondary mass-radius relationship, the minimum period was deduced to be of order half an hour. The power-law fit underestimates somewhat the period at the low-mass end. Depending upon the precise composition, the lower limit for hydrogen-rich homogeneous secondaries from explicit stellar models (Bodenheimer 1971) could be in the range of ~45 ± 15 minutes. We briefly review the reasons for this limit and introduce a useful new $P\sqrt{\rho}$ relationship.

We shall refer to the lobe-filling component as the secondary. Let μ be the mass fraction $M_2/(M_1 + M_2)$. Then it may be shown that the mean size of the Roche lobe R_L is related to the separation D by

$$R_L/D = 0.459\mu^{1/3} \tag{1}$$

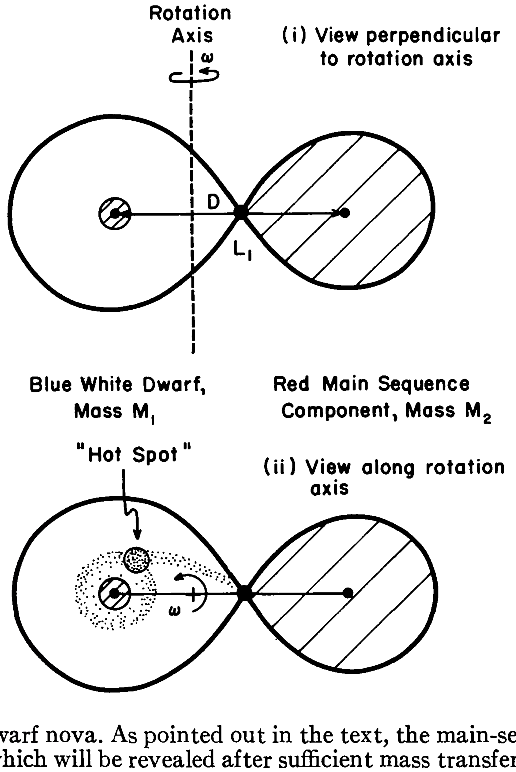

FIG. 1.—The typical dwarf nova. As pointed out in the text, the main-sequence component may contain a small helium core, which will be revealed after sufficient mass transfer. In later stages, as proposed for AM CVn, the main-sequence component is replaced by a degenerate, receding system, mass transfer still proceeding as shown.

where, provided $\mu < 0.5$, the errors do not exceed ~3 percent. Combined with Kepler's law, this gives a relationship independent of the total mass of the system,

$$\langle\rho_2\rangle = \frac{3M_2}{4\pi R_L^3} = \frac{3\pi}{(0.459)^3}\frac{1}{GP^2}, \quad \text{i.e.,} \quad P\sqrt{\langle\rho_2\rangle} = 3.83 \times 10^4, \tag{2}$$

where $\langle\rho_2\rangle$ is measured in grams cm^{-3}, and the period P is in seconds. Note that since the star (i) is slightly distended, and (ii) cannot exceed the size of its surrounding Roche lobe, the mean density $\langle\rho_2\rangle$ is actually a lower limit on the mean density of a corresponding nonrotating star, whether or not it fills the lobe. For AM CVn we find $\langle\rho_2\rangle \sim 1.3 \times 10^3$ g cm^{-3}.

Periods given by equation (2) are shown in figure 2 for lobe-filling secondaries, with several mass-radius relationships of interest. As a zero-age main-sequence (ZAMS) secondary loses mass, it travels down the ZAMS relationship, eventually transferring, when hydrogen burning ceases, to the degenerate sequence. The approximate intersection of these two relationships gives the minimum period for a homogeneous hydrogen-rich secondary.

It is immediately clear that the secondary of AM CVn, with $P = 1051.0505 \pm 0.0005$ s (Warner and Robinson 1972), cannot, if homogeneous, contain hydrogen (the degenerate case with $M_2/M_\odot \sim 0.2$–0.3 can safely be ignored since, in practice, one could not assemble the material without ignition). This prediction of the absence of hydrogen is substantiated by the spectrum. Warner and Robinson attribute He I line-doubling to weak ring or hot-spot emission superposed upon a normal DB absorption spectrum. Thus helium is observationally involved in the mass transfer; of hydrogen there appears to be no sign.

From figure 2, two obvious helium candidates suggest themselves: (i) a helium ZAMS

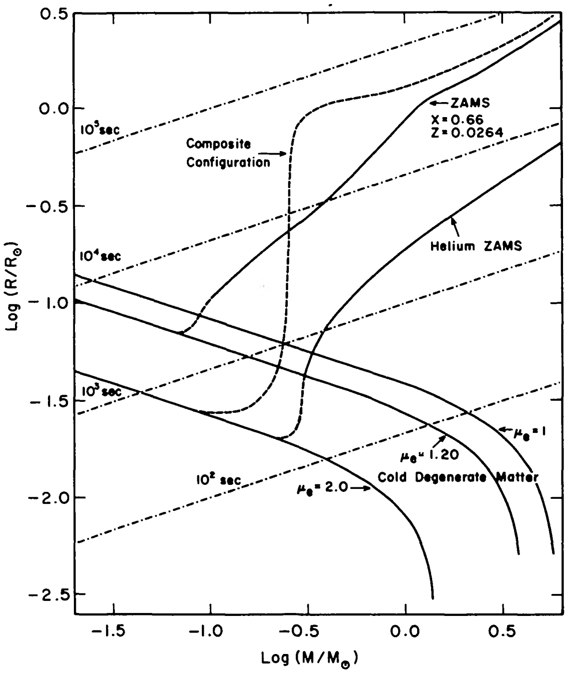

FIG. 2.—Lines of given period are shown for lobe-filling secondaries, together with typical hydrogen- or helium-burning zero-age main sequences and a schematic representation of the possible relationship for a composite configuration. Because of mass loss, evolution proceeds to the left along any sequence, where a transition ultimately occurs to the appropriate degenerate sequence.

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model with $M_2 \sim 0.4$–$0.5\ M_\odot$ and (ii) a degenerate helium low-mass white dwarf with $M_2 \sim 0.041\ M_\odot$ (using the Chandrasekhar equation of state). The first is easily dismissed. It would dominate the spectrum and, for a reasonable mass of the observed white-dwarf primary, give huge radial-velocity variations. The second alternative seems to be the natural conclusion. It commends itself to us for almost precisely the same reasons which led Ostriker and Hesser to dismiss it. However, the existence of the hot spot and partially opaque ring are crucial new features of the model, since eclipses of the spot can occur both by the ring and by the relatively large and dark body.

Assuming that $M_2 \sim 0.041\ M_\odot$, a good range of primary masses is covered by the two values of $\mu = 1/8$ and $1/27$ (chosen for computational convenience). The results are given in table 1. The primary orbital velocity range is of great interest. Kraft (1972) has kindly informed us that he has a multiple-trailed 200-inch (508-cm) prime-focus spectrogram of AM CVn on which it appears that there may be some variation of the helium-line positions at the limit of detectability. This implies a possible orbital velocity projection of ~50–60 km s^{-1}, i.e., the mean of our tabulated values.

The rate of mass transfer is slightly higher than that attributed to WZ Sge. From the fact that one can see the DB absorption lines, from the weakness of the emission lines, and from the amplitude of the high-frequency flickering, the bright spot evidently contributes ~10 percent of the white-dwarf flux in the blue region. Taking typical white-dwarf radii, and using Wampler's estimated effective temperature, one concludes that ~1–10 percent of the kinetic energy of infalling material is radiated in this region. If $T_{\rm spot}$ is also $\sim 2 \times 10^4\ ^\circ$K in the visible region, one finds a typical dimension of the spot $r_{\rm sp} \sim 3 \times 10^8$ cm. The usual angular-momentum considerations suggest that the radius of the orbiting disk is $r_d \sim 4$–8×10^9 cm. Thus $r_{\rm sp}/r_d \sim 0.04$–0.08. In U Gem (Warner and Nather 1971), $r_{\rm sp}/r_d \sim 0.05$ from eclipse information. This supports the suggestion that many of the properties of these systems may be very simply scaled up or down.

Because of mass transfer, low μ, and the nonrelativistic degeneracy mass-radius relation, the general theory gives $P^{-1}dP/dt \approx -M_2^{-1}dM_2/dt$. The period should therefore be increasing by one or two parts in 10^8 per annum, a rate approximately three orders of magnitude below the present observational limit. It is worth noting explicitly that these results appear to answer a question raised by Faulkner (1971): tidal torques transferring angular momentum evidently can prevent a disrupting degenerate secondary from becoming secularly unstable. Evolution with a degenerate secondary then occurs with an increasing separation and period. A consequence of this remark is that the components of AM CVn were previously closer than they now are.

How does such a system arise? We now recognize that it may well be possible for nuclear evolution of the original secondary to have proceeded prior to substantial mass transfer taking place. When the latter effects begin to dominate, the nuclear evolution is slowed down or frozen, and it is possible that some of the known cataclysmic or dwarf novae do indeed have substantial helium cores with mass ~ 0.08–$0.12\ M_\odot$, say. If and

TABLE 1

THE PROPERTIES OF AM CANUM VENATICORUM ASSUMING $M_2 = 0.041\ M_\odot$

Parameter	$\mu=1/8$	$\mu=1/27$
$M_1/M_\odot$	0.29	1.07
D (cm)	1.07×10^{10}	1.60×10^{10}
$V_{\rm orb}(M_1)$ (km s^{-1})	80	35
$-dM_2/dt$ ($M_\odot$ per year)	4.5×10^{-10}	9.2×10^{-10}
$P^{-1}dP/dt \approx -M_2^{-1}dM_2/dt$ (per year)	1.1×10^{-8}	2.2×10^{-8}

when the final vestiges of the hydrogen-rich envelope have been transferred, ending the nova phase of evolution, a degenerate helium core will be left for further whittling down as suggested above. The mass $M_2 \sim 0.041\, M_\odot$ is consistent with this suggestion. Furthermore, without a mechanism as ubiquitous as gravitational radiation, it is difficult to see how one could produce objects of any reasonable mass orbiting at the separations ($\lesssim \frac{1}{4}\, R_\odot$) suggested by the period.

According to this interpretation, one further prediction can be made: AM CVn will never again suffer a nova outburst, since no hydrogen remains for thermonuclear subsurface ignition. It is the first example of a new class of variable stars—the postcataclysmic novae.

For completeness, one further point should be mentioned. The radius R_I of an inhomogeneous star with a small helium core will be somewhat larger than that, R_H, of a homogeneous hydrogen-rich star. Although, via mass-loss, R_I/R_H will ultimately become quite small, it may not necessarily do so monotonically. While hydrogen continues to burn outside the hypothesized core, the star will, through mass loss, appear progressively more evolved from a fractional mass point of view. At some stage hydrogen burning ceases; whether with a bang or a whimper is difficult to say. Subsequently a rapid envelope contraction will ensue which may produce a degenerate inhomogeneous star lying well within the Roche lobe. Gravitational radiation then reduces the size of the system without mass transfer until the Roche lobe once more encroaches upon the secondary. If, on the other hand, the envelope collapse envisaged above were sufficiently slow, one could conceivably expect to find a short-lived phase in which a period of $\sim 10^3$ seconds was permitted. The observations seem to rule this out for AM CVn since, in other novae, hydrogen emission dominates that from helium by one or two orders of magnitude and there seems, from visual inspection, to be no evidence for any hydrogen-line emission in AM CVn. However, a careful observational limit on possible hydrogen-line emission would not be without interest. We expect the timescales to the AM CVn stage to be dominated by the earlier parts of the evolution, and to be comparable to those of the standard model. We sketch in figure 2 a possible mass-radius relationship for the composite configuration envisaged in this paragraph. Detailed results must await the construction of appropriate stellar models.

We are much indebted to Robert P. Kraft for helpful conversations. One of us (B. P. F.) is grateful for support from an IBM predoctoral fellowship.

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