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DQ HERCULIS: WEAK SISTER TO HZ HERCULIS

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ABSTRACT

We have explored a model for DQ Her in which a strongly magnetic degenerate dwarf accretes matter from its companion in a close binary system. We find that the model can explain major photometric and spectroscopic features of the system, including (i) the relative (visual) luminosities of the degenerate dwarf, of the disk, and of the companion star, (ii) the relative amplitude and pulse profile of the 71^s periodicity, and (iii) the high effective temperature and relatively low luminosity of the degenerate dwarf. We predict that the rotation period of the degenerate dwarf is 142^s, and that consequently (i) the polarization of the emitted radiation may rotate through 360° each 142^s and (ii) it is likely that detailed photometric observations can distinguish, at some level, between alternate pulses. Finally, we speculate that the magnetic field in DQ Her is an internal fossil field exposed by an earlier nova outburst.

Subject headings: binaries — magnetic fields — novae — polarization — pulsation — white dwarf stars

I. INTRODUCTION

Photometric observations (Walker 1954) established that the nova DQ Herculis (1934) belongs to an eclipsing binary system with period $P_b = 0^d.1936$ (4^h39^m). Subsequent spectroscopic observations (Kraft 1958; Greenstein and Kraft 1959) implied that the components of the system are a degenerate dwarf and a red dwarf (Kraft 1959), and that mass exchange and loss are occurring in the system. Indeed, the strong emission line He II (λ4686) shows a velocity variation which can be interpreted as orbital motion with $K \simeq 150$ km s^{-1}, and the classical rotational disturbance displayed by the He II velocity curve before and after mideclipse indicates that a gaseous ring or disk around the degenerate dwarf dominates the visual luminosity (Kraft 1959).

Further photometric observations (Walker 1956, 1958, 1961; see also Nather and Warner 1969; Warner *et al.* 1972) revealed a strictly periodic ($71^s.1$ periodicity) small-amplitude ($\Delta M = 0.02$–0.05) component in the flickering observed outside eclipse. The recent discovery that DQ Her exhibits linear polarization that varies with the $71^s.1$ periodicity (Nather, Smak, and McGraw 1974) suggests that rotation of a strongly magnetic degenerate dwarf provides the underlying clock for the $71^s.1$ periodicity. This, together with the earlier evidence for mass exchange and for the presence of an accretion disk around the degenerate dwarf, implies that DQ Her is intimately related to current models of the X-ray pulsars Cen X-3 and Her X-1 (= HZ Her) (Giacconi *et al.* 1974) in which a rotating, strongly magnetic compact object accretes matter from its companion in a close binary system (Pringle and Rees 1972; Davidson and Ostriker 1973; Lamb, Pethick, and Pines 1973; Lamb and Van Horn 1973).

In this *Letter* we explore such a model for the DQ Her system. We postulate that the physical environment (in particular the rate of mass accretion) of the compact object is not far different from that found in its Hercules neighbor, HZ Her. Then, according to this picture, the marked contrast in the characteristics of the two systems (for example, the 10,000-fold difference in total luminosity) arises from the fact that the role of compact object in the DQ Her system is taken by a degenerate dwarf rather than by a neutron star.

Below, we first consider optical observations of the $71^s.1$ periodicity which strongly indicate that the true rotation period of the degenerate dwarf is $P = 142^s.2$. We next describe the parameters of our model, and relate the resulting characteristics to previous photometric and spectroscopic observations. We remark on the possible significance of DQ Her for the class of cataclysmic variables, and conclude by presenting several observational tests of our model.

II. ROTATION

One of the most enigmatic features of the $71^s.1$ periodicity is the apparent $+360°$ phase shift which occurs through eclipse (Warner *et al.* 1972). This phase shift combined with the time-varying linear polarization would appear to exclude simple rotational, as well as the earlier pulsational, models for the periodicity (Walker 1958, 1961; Kraft 1963; Baglin and Schatzman 1969; Warner *et al.* 1972). Bath, Evans, and Pringle (1974) considered whether a knife-edge eclipse of the degenerate dwarf, rotating with a period $P = 142^s.2$, could account for the observed phase shift. They concluded that the magnitude of the phase shift could be reproduced, but that the sign would be opposite to that observed; the model was consequently ruled out.

Here we reconsider the problem and demonstrate that emission from the two magnetic poles of a degenerate dwarf rotating with period $P = 142^s.2$, if modulated by a smooth and relatively slowly varying ($A/\dot{A} > P$) eclipse function $A(t)$, can account for the observational data. In analogy with Warner *et al.* (1972), we write the observed intensity of the source as $I(t) = A(t)\,|\cos(\omega t)|$ and fit to this a function of the form $I^*(t) = A^*|\cos[\omega t + \delta(t)]|$ where $P = 2\pi/\omega = 142^s.2$.[1]

[1] The pulsed contribution from the degenerate dwarf is always nonnegative. Our use of absolute value signs represents a nontrivial modification of the expressions used by Warner *et al.* (1972),

If we derive the parameters of the fit by requiring that a local maximum of the fitted curve coincide with a local maximum of the observed curve, then the phase shift δ is given by

$$\tan\delta = -\dot{A}/(\omega A)\,. \tag{1}$$

Since $\dot{A} < 0$ for binary phase $0.9 < \phi < 1.0$, while $\dot{A} > 0$ for $0.0 > \phi > 0.1$, the phase shift δ smoothly increases from 0° to 90° during ingress and from −90° to 0° during egress. The phase shift through eclipse is then −180°, but the net phase shift through the orbital period is zero; this behavior is analogous to the classical rotational disturbance of radial velocities. However, because the observed intensity peaks occur with frequency 2ω, to the extent that the characteristics of emission from the two magnetic poles are identical there is an aliasing problem in the observational data: we are allowed to shift the posteclipse data relative to the pre-eclipse data by any multiple of $2\pi/2\omega = 71^{s}.1$. We suggest that the phase shift displayed by Warner *et al.* (1972, their fig. 4) is measured relative to the emission peak from *one* magnetic pole of the degenerate dwarf during ingress, but relative to the emission peak from the *other* pole during egress, thus creating an apparent phase shift +180° (or +360° in their notation, since $2\pi/2\omega = 71^{s}.1$). The altered display of the phase shift data suggested by our interpretation is shown in figure 1*a*.

Since the eclipse is at nearly grazing incidence (Kraft 1959; Warner *et al.* 1972), in some cases it may be possible to trace the phase shift through eclipse. Our model then predicts that following ingress δ should decrease rapidly, passing through zero at mideclipse [see eq. (1) with $\dot{A}$(mideclipse) > 0] and joining on smoothly to the egress data. This behavior might explain the two seemingly discordant phase shifts near mideclipse referred to by Warner *et al.* (1972). Quantitative agreement of the average behavior of the phase shift with our proposed model might be checked by constructing a smoothed template for $A(t)$ from observations like those shown in figure 1*b*, giving $\delta(t)$ through equation (1).

Since we are out of the plane of the binary system ($i \sim 77°$), the twofold symmetry of the degenerate dwarf's dipole magnetic field is broken unless its magnetic moment $\boldsymbol{\mu}$ is perpendicular to the rotation axis (we assume that the rotation axis of the degenerate dwarf is aligned with that of the binary system). Even in the latter case, emission from the two poles might be distinguishable if a longitudinal and/or transverse displacement of $\boldsymbol{\mu}$ relative to the center of the star exists, as seems to be indicated in a number of magnetic stars (see, e.g., Finn and Kemp 1974). Furthermore, since the emitted radiation is produced and propagates through regions with a strong magnetic field, we may expect the pulsed emission to display significant polarization. Then a simple geometrical model (the magnetic field is not expected to markedly alter the opacity in the visible unless $B > 10^{8}$ gauss, and the accreting matter is optically thin to the emitted radiation; see below) suggests that the polarization vector may rotate through 360° over the period $P = 142^{s}.2$. From the foregoing discussion, it seems likely that emission from the two magnetic poles can be distinguished observationally at some level.

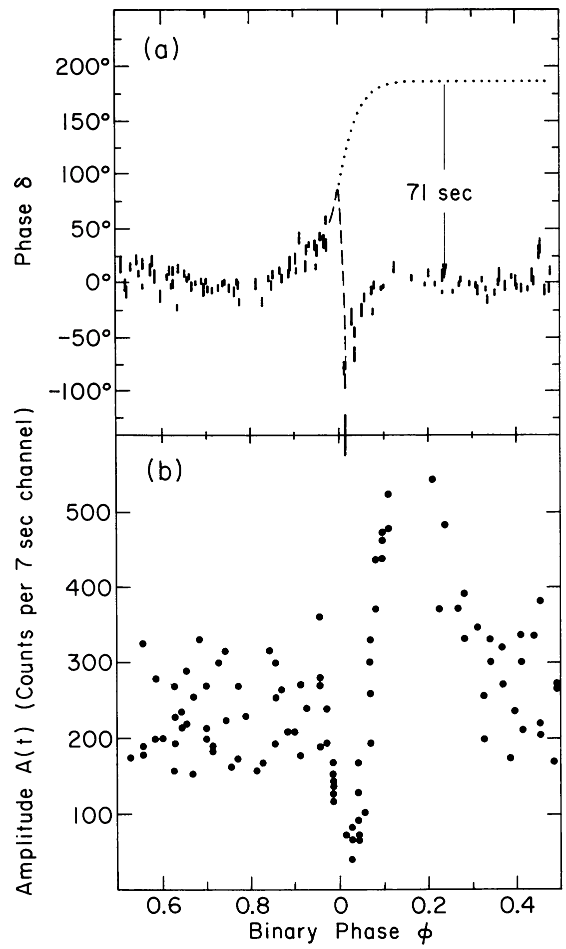

FIG. 1. (*a*) *Altered* display of phase determinations of the 71^{s} periodicity as a function of position in the orbital cycle of DQ Her. The dotted line shows the position of the posteclipse data as plotted by Warner *et al.* (1972); the dashed line shows the character of the predicted phase variation if in some cases it is possible to trace the phase through mideclipse. (*b*) Amplitude variations of the 71^{s} periodicity around the orbital cycle. Both sets of observational data are after Warner *et al.* (1972).

III. MODEL FOR DQ HERCULIS

For the sake of definiteness, we assume the parameters of the DQ Her system derived by Kraft (1959); then the components of the binary are a low-mass degenerate dwarf ($M = 0.25\ M_{\odot}$, $R = 1.5 \times 10^{9}$ cm) and a red dwarf ($M = 0.27\ M_{\odot}$, $R = 2.7 \times 10^{10}$ cm). Warner (1973) has recently suggested larger masses for both components of the system, but for our purposes the difference is only slight. The separation a is 8×10^{10}

since it changes the maximum possible phase shift given by the model.

cm, giving a radius 3×10^{10} cm for the inner Lagrangian surface of the red dwarf that is only 15 percent more than its radius. Thus, within the observational uncertainties, the red dwarf fills its Roche lobe and can transfer mass through the inner Lagrangian point L_1. For the strength of the degenerate dwarf's magnetic field, we take a surface value $B_0 = 10^8$ gauss that is indicated for several of the other magnetic degenerate dwarfs (Lamb 1973); then $\mu = B_0 R^3 = 10^{35}$ gauss cm^3.

Our analysis (and notation) closely follows that in Lamb *et al.* (1973). We postulate that the mass accretion rate in DQ Her, although possibly varying substantially with time, is on average $\dot{M} \sim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$, a value that is not too different from that indicated for the HZ Her system. Such a value also agrees with the mass transfer rate given by evolutionary calculations in which gravitational radiation removes angular momentum from the system (Paczyński 1967; Faulkner 1971). Then the (pulsed) luminosity of the degenerate dwarf is

$$L = 1 \times 10^{33}(\dot{M}/10^{-10}\ M_\odot\ \mathrm{yr}^{-1})(M/M_\odot)R_9^{-1}\ \mathrm{ergs\ s^{-1}}\,, \qquad (2)$$

where M is the mass and R_9 the radius, in units of 10^9 cm, of the degenerate dwarf. Nuclear reactions can potentially liberate $\sim$10 times as much energy as that given by equation (2); however, for the relatively low accretion rate we postulate, the temperatures and densities at the surface of the degenerate dwarf, even at the magnetic poles, are not sufficient to burn the accreting matter at once. The accreted matter may, however, contribute to a future nova outburst (Starrfield *et al.* 1972; Starrfield, Sparks, and Truran 1974).

If we determine the Alfvén surface (Lamb *et al.* 1973) by balancing the magnetic field energy density $B^2/8\pi$ against the rotational energy density $\frac{1}{2}\rho r_A{}^2\Omega^2$ of matter at the inner edge of the disk, we find

$$\begin{aligned} r_A(\mathrm{orbital}) &\simeq (v_r/v_{ff})^{2/7} r_A(\mathrm{radial}) \\ &\simeq 7 \times 10^{10}(v_r/10^{-2}v_{ff})^{2/7} \\ &\quad \times \left[\frac{\mu_{35}{}^{4/13}P_2{}^{4/13}(M/M_\odot)^{3/13}}{L_{33}{}^{2/13}R_9{}^{2/13}}\right]\ \mathrm{cm} \end{aligned} \qquad (3)$$

where v_r and v_{ff} are the radial and free-fall velocities of matter at the Alfvén surface: μ_{35} is the magnetic moment, in units of 10^{35} gauss cm^3, L_{33} is the luminosity in units of 10^{33} ergs s^{-1}, and P_s is the rotation period, in units of 10^2 s, of the degenerate dwarf. Such a value for r_A (orbital) is comparable to the separation between the components of the binary system and exceeds the radius of the degenerate dwarf's Roche lobe.

The corotation radius r_c, at which the centrifugal and gravitational forces will just balance if a particle is corotating with the degenerate dwarf, is given by

$$r = 3.2 \times 10^9 P_2{}^{2/3}(M/M_\odot)^{1/3}\ \mathrm{cm}\,. \qquad (4)$$

From equations (3) and (4), we see that even for $v_r \sim 10^{-2}\ v_{ff}$ and a much larger luminosity (i.e., mass accretion rate) than that in equation (2), we have $r_A \gg r_c$. Thus, we are dealing with a "fast rotator" (Lamb *et al.* 1973). In such a case, matter tends to accumulate on field lines that extend beyond r_c. Although this may continue for a time, eventually the density of matter will become so great that the magnetic field will be unable to enforce corotation and the outer regions of the magnetosphere will become unstable (Roberts and Sturrock 1973).

While the extent to which the magnetosphere can extend beyond r_c, is, at present, an open theoretical question, the observational evidence for a rather dense accretion disk around the degenerate dwarf in DQ Her, with characteristic outer radius 2×10^{10} cm, (Kraft 1959) argues that indeed the magnetic field does not extend much beyond r_c for any substantial length of time. In DQ Her, turbulent interaction of the magnetosphere with matter at the inner edge of the disk could make a significant contribution to the flickering observed outside eclipse. As the foregoing discussion indicates, DQ Her may provide an opportunity for detailed observational exploration of a "fast rotator."

With $M = 0.25\ M_\odot$ and $P = 142^s$, equation (4) gives $r_c/R > 3$; for a higher-mass degenerate dwarf, this ratio becomes larger, so that even for the minimum Alfvén radius (r_c) we have $r_A \gg R$. In these circumstances we expect that the magnetic field will have an opportunity to direct the inflow of accreting matter toward the two magnetic poles. Using the last field line closing inside r_A to estimate the surface area, and the fact that the total luminosity cannot exceed the blackbody value, we obtain as a lower limit for the temperature T_e (pole) of the emitting region,

$$T_e(\mathrm{pole}) > 1.7 \times 10^5 (M/M_\odot)^{1/28}\mu_{35}{}^{1/7}L_{33}{}^{5/28}R_9{}^{-23/28}\ {}^\circ\ \mathrm{K}\,. \qquad (5)$$

DQ Herculis is thus an "ultraviolet pulsar"; since the emitted radiation originates in and propagates through regions with a strong magnetic field, the pulses may be significantly polarized, as noted earlier.

We expect electron scattering to be the dominant source of opacity; the optical depth from the stellar surface, vertically through the accretion column, is then

$$\tau \simeq 3 \times 10^{-2}(M_\odot/M)^{3/2}(r_A/10^{10}\ \mathrm{cm})L_{33}R_9{}^{-1/2}\,. \qquad (6)$$

Consequently, the accretion column has little effect on the angular distribution of emitted radiation, and we may expect the observed emission to be modulated principally by the varying angle which the stellar surface at the magnetic poles makes with the line of sight. The pulse profile might then closely resemble a $|\cos \omega t|$ curve, as observations indicate (Nather and Warner 1969; Warner *et al.* 1972).

Finally, we can estimate a lower bound to the luminosity of the disk, the dominant source in the visual, from equation (2) by taking $R_9 = 10$; this gives $L(\mathrm{disk}) \simeq 10^{32}$ ergs s^{-1}. Continuum and line emission from the disk due to the absorption and reradiation of pulsed ultraviolet light from the degenerate dwarf will supplement this. We expect a characteristic temperature for the disk of T_e (disk) $\simeq 2 \times 10^4\ {}^\circ$ K.

IV. COMPARISON WITH OBSERVATIONS

How well does our model agree with the photometric and spectroscopic observations of DQ Her? The expansion parallax of the nebula (Baade 1940; Walker 1956) gives $M_V = +7.4$ for the disk outside eclipse, which agrees with our value $L(\text{disk}) \simeq 10^{32}$ ergs s^{-1}. One puzzling feature of the system has been that spectroscopic observations imply that the temperature of the degenerate dwarf exceeds 8–12 $\times 10^4$ ° K, yet at the same time $L_{\text{visual}} < 10^{-1.5} L_\odot$ ($M_V > +8.5$), leading to a discrepancy with degenerate dwarf radii greater than a factor 2–4 (Kraft 1959). This now can be understood, in the present model, in terms of the degenerate dwarf's strong magnetic field which confines the accreting matter and leads to emission from only a small fraction of the stellar surface at the two magnetic poles. The emitted radiation consequently has a relatively low luminosity and yet a high effective temperature ($T \gtrsim 1.7 \times 10^5$ ° K). Using the Rayleigh-Jeans distribution $L \sim (\nu/\nu_{\max})^3$ to scale the luminosity of the degenerate dwarf from the ultraviolet to the visual, we find $L_{\text{visual}}/L(\text{disk}) \simeq 10^{-2}$. This is in good agreement with the observed ~2–5 percent relative amplitude of the $71^{\text{s}}.1$ pulsed emission.

The companion in the system is not observed photometrically or spectroscopically, even at eclipse, giving an upper limit $L(\text{star}) < 2.5 \times 10^{-2} L_\odot$ ($M_V > +9$). Its presence near the degenerate dwarf, however, allows us to place a severe upper limit on the luminosity of the latter. With the assumed dimensions of the binary system and of the companion, the latter subtends a solid angle $\phi_{\text{star}} \simeq 0.4$ as seen from the degenerate dwarf. If we make the additional conservative assumption that a fraction $\alpha = 0.1$ of the ultraviolet radiation incident on the companion is absorbed, we have

$$L < L_{\max} = \alpha(4\pi/\phi_{\text{star}})L(\text{star}) \simeq 1 \times 10^{34} \text{ ergs s}^{-1}, \quad (7)$$

which is consistent with the value given by equation (2).

Bath *et al.* (1974) have proposed a model for DQ Her that is qualitatively similar to the present model. However, based on preliminary observations of the spin-up time scale for the degenerate dwarf ($P/|\dot{P}| \simeq 5 \times 10^5$ years [Herbst and Ostriker 1971]), they employed a mass accretion rate $\dot{M} = 2 \times 10^{-8} M_\odot$ yr^{-1}, which leads to a degenerate dwarf luminosity $L \simeq 2 \times 10^{35}$ ergs s^{-1}. Such a high luminosity seems ruled out by the upper limit derived above. The relationship between mass accretion rate and changes in the rotation period may be quite complex, however (Lamb and Pethick 1974), particularly because DQ Her is a fast rotator.

From the foregoing analysis, it appears quite likely that nature has provided us, in the systems DQ Her and HZ Her = Her X-1, with an opportunity to study the contrasting behavior of a degenerate dwarf and a neutron star in similar physical environments; table 1 compares possible model parameters for the two systems.

TABLE 1

COMPARISON OF MODEL PARAMETERS FOR DQ HERCULIS AND HZ HERCULIS (= Her X-1)

Quantity	DQ Her	HZ Her
Compact object	Degenerate dwarf	Neutron star
Companion	Red dwarf	Subgiant
Mass accretion rate ($M_\odot$ yr^{-1})	$\sim 10^{-10}$	$\sim 10^{-9}$
Rotation period P (s)	142	1.24
Binary period P_b (days)	0.194	1.70
L(compact object) pulsed (ergs s^{-1})	$\sim 10^{33}$	$\sim 10^{37}$
T_e(pole) (° K)	$\gtrsim 1.7 \times 10^5$	$\gtrsim 5 \times 10^7$
L(disk) (ergs s^{-1})	$\approx 10^{32}$	$\approx 10^{35}$

Finally, we speculate that the strong magnetic field of the degenerate dwarf in DQ Her was exposed by the loss of its envelope in an earlier nova outburst. Such a possibility lends further support to the attractive hypothesis that many of the magnetic degenerate dwarfs are formed by exposure of a strong internal fossil field (Fontaine, Thomas, and Van Horn 1973), either by the continuous ejection of a nebular shell, as in the case of planetary nuclei (Van Horn and Hansen 1974), or in the explosive ejection of the envelope, as in the case of novae. If, as is believed, dwarf novae do not eject any substantial fraction of their envelope during an outburst, then according to the above hypothesis they might not exhibit strong external magnetic fields. However, polarization studies of old novae might expand the as yet meager list of known magnetic degenerate dwarfs.

V. CONCLUDING REMARKS

We have explored a model for DQ Her in which a strongly magnetic degenerate dwarf accretes matter from its companion in a close binary system. We find that the model can explain major photometric and spectroscopic features of the system, including (i) the relative (visual) luminosities of the degenerate dwarf, of the disk, and of the companion star, (ii) the relative amplitude and pulse profile of the 71^{s} periodicity, and (iii) the high effective temperature and relatively low luminosity of the degenerate dwarf. We predict that the rotation period of the degenerate dwarf is 142^{s}, and that consequently (i) the polarization of the emitted radiation may rotate through 360° each 142^{s}, and (ii) it is likely that detailed photometric observations can distinguish, at some level, between the emission from the two magnetic poles. Finally, we speculate that the strong magnetic field of the degenerate dwarf in DQ Her is an internal fossil field exposed by an earlier nova outburst. Consequently, polarization studies of other old novae may add to the list of known magnetic degenerate dwarfs.

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Note added 19 July 1974. Independent discovery of time-varying linear and circular polarization in DQ Her has now been reported by Kemp and Swedlund (1974). They report that a substantial fraction of the circular polarization varies modulo 142^s, indicating that this is the actual rotation period of the degenerate dwarf.

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