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The DQ Herculis Stars

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ABSTRACT. We review the properties of the DQ Herculis stars: cataclysmic variables containing an accreting, magnetic, rapidly rotating white dwarf. These stars are characterized by strong X-ray emission, high-excitation spectra, and very stable optical and X-ray pulsations in their light curves. There is considerable resemblance to their more famous cousins, the AM Herculis stars, but the latter class is additionally characterized by spin–orbit synchronism and the presence of strong circular polarization. We list eighteen stars passing muster as certain or very likely DQ Her stars. The rotational periods range from 33 s to 2.0 hr. Additional periods can result when the rotating searchlight illuminates other structures in the binary. A single hypothesis explains most of the observed properties: *magnetically channeled accretion within a truncated disk.* Some accretion flow still seems to proceed directly to the magnetosphere, however. The white dwarfs' magnetic moments are in the range 10^{32}–10^{34} G cm^3, slightly weaker than in AM Her stars but with some probable overlap. The more important reason why DQ Hers have broken synchronism is probably their greater accretion rate and orbital separation. The observed L_x/L_V values are surprisingly low for a radially accreting white dwarf, suggesting that most of the accretion energy is not radiated in a strong shock above the magnetic pole. The fluxes can be more satisfactorily explained if most of the radial infall energy manages to bypass the shock and deposit itself directly in the white dwarf photosphere, where it should emerge as EUV radiation. This also provides an adequate source of ionizing photons to power the high-excitation optical and UV emission lines. This is probably the DQ Her analog to the famous "soft X-ray excess" in AM Her stars. However, unlike the AM Her case, this radiation has not been directly observed, so the analogy must not (yet) be embraced too firmly. There is some conventional wisdom today which segregates the short-period from the long-period DQ Her stars. But the observational grounds for this distinction are slim, except in one respect: X-ray emission from short-period systems appears to be weaker and softer. This must be due to the shallower depth of the potential well, and/or the greater difficulty the fast rotators have in enforcing radial accretion flow.

1. INTRODUCTION

Forty years ago, studying the light curve of the remnant of Nova Herculis 1934 (=DQ Herculis), Merle Walker found strictly periodic variations with the amazingly short period of 71 s (Walker 1954, 1956). Twenty years later, the discovery of X-ray pulsars and the success of the rotating neutron-star model in accounting for their properties led a gaggle of theorists to propose that the pulsation in DQ Her also arose from the rapid rotation of an accreting compact star, with a white dwarf replacing the usual neutron star (Lamb 1974; Katz 1975; Bath et al. 1974; Herbst et al. 1974). Since radial accretion into the deep gravitational potential well of the white dwarf ought to produce hard X-rays, all agreed that DQ Her ought to be detected as a weak pulsed X-ray source.

This expectation was not fulfilled when a sensitive observation in the 0.1–4.0 keV bandpass was carried out by the *Einstein* Observatory (Córdova et al. 1981). However, by that time three other pulsating X-ray sources had been discovered, with properties much more closely resembling cataclysmic variables than garden-variety X-ray binaries (AE Aquarii, AO Piscium, V1223 Sagittarii; see references below). Hence it seemed likely that such a *class* does exist, whether or not DQ Her itself was a member. Furthermore, the discovery of the AM Herculis stars, in which observation showed radial accretion flow, hard X-ray emission, and polarized optical radiation indicative of strong magnetic fields, did provide some confirmation of these ideas.

Direct evidence for a magnetic field in the DQ Her stars remained elusive until the observations of BG Canis Mi-

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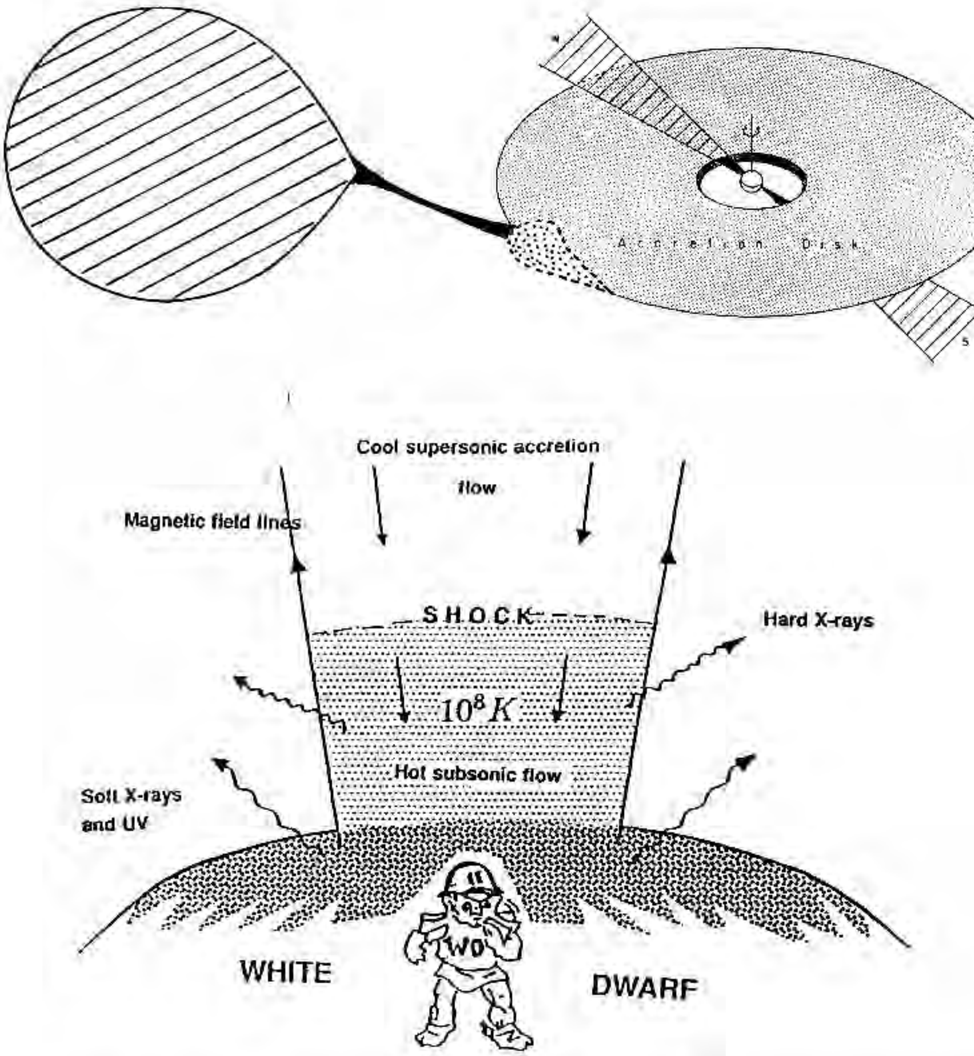

FIG. 1—*Upper frame*: meet a DQ Her binary. The bloated region at the outer edge of the disk is the traditional "hotspot" where the mass-transfer stream strikes the disk. The white dwarf rotates rapidly, and its field lines carve out a magnetic cavity in the disk. *Lower frame*: up close and personal, near the accreting magnetic pole. The infalling gas encounters a shock and radiates its energy in hard X rays. The white dwarf photosphere is heated by the hard X rays, and directly by whatever gas manages to avoid the shock.

noris revealed circular polarization, strongly suggesting the presence of a $\sim 4\times10^6$ G field (Penning et al. 1986; West et al. 1987). Polarization has also been observed in RE 0751+144 (Piirola et al. 1993). These studies have now finally established the basic correctness of the magnetic rotator model for this class.

Here I present a census and review of the DQ Her stars, complete as of mid-1993. I have tried to bring a reporter's instinct to the quirks of individual stars, about which the original research papers testify in much detail, and a zoologist's instinct to the unifying themes, which the papers say little about. Then I have assumed the reporter to be in the employ of the zoologist, in order to contain the sheer volume of information. Whether this works depends on the zoologist's judgment, of course.

The DQ Her class represents only about 5%–10% of cataclysmic variables (hereafter referred to as CVs). Accordingly, there is really only one previous review article (Berriman 1988). This contrasts to a healthy supply of general reviews on CVs (Warner 1976; Robinson 1976; Wade and Ward 1985; Warner 1987; Córdova 1993). More specialized reviews relevant to the present topic may be found on magnetic white dwarfs (Schmidt and Liebert 1987; Chanmugam 1992) and AM Herculis stars (Liebert and Stockman 1985; Beuermann 1988; Mukai 1988; Cropper 1990).

2. DRAMATIS PERSONAE

2.1 The Fundamental Model

The basic idea of a DQ Her star, as envisioned by the theory papers of the mid-1970s, is shown in the upper part of Fig. 1. A late-type star fills its Roche lobe and transfers matter to a magnetic white dwarf. As gas starts to fall inward, it has too much angular momentum to accrete directly, and hence spirals through an accretion disk. At some point the kinetic energy density ρv^2 of the gas is locally exceeded by the magnetic energy density $B^2/8\pi$, and within this radius the infalling gas will be guided along field lines to accrete radially onto the white dwarf. For spherical accretion it is easy to calculate this transition radius, because v is simply the free-fall velocity $(2GM/r)^{1/2}$; the result is

$$R_A = 3.7\times 10^9 \text{ cm } \dot{M}_{17}^{-2/7}\ M_1^{-1/7}\ \mu_{32}^{4/7}, \qquad (1)$$

where R_A is the "Alfven radius," $\dot{M}_{17}$ is the accretion rate in units of 10^{17} g s^{-1}, M_1 is the white dwarf mass in $M_\odot$, and μ_{32} is the white dwarf's magnetic moment in units of 10^{32} G cm^3. For *disk* accretion, the magnetospheric radius should be slightly smaller; theoretical estimates suggest $R_{\rm mag}\approx 0.5\ R_A$ (Lamb 1988).

The release of accretion energy creates an intense bright spot at or above the white dwarf's magnetic poles. If the white dwarf's spin and magnetic axes are not aligned, then the star is an "oblique rotator" and should produce a modulation in X-ray/UV/optical light as it wheels its little lighthouse beam around the sky. This model underlies essentially all research on these stars, and so is useful to present at the outset.

It is also true that some fraction of the lighthouse beam (not "beamed" in the sense of radio pulsars, but only into 2π sr) will fall upon structures in orbit around the white dwarf. For example, both the secondary star and the bright spot at the outer edge of the disk are likely to intercept a few percent of the white dwarf's accretion luminosity, and the consequent heating is periodic since the lighthouse beam wheels rapidly around. But the heating occurs at a slightly lower frequency, assuming that the spin is prograde to the orbit. In particular, the heated target will be illuminated one less time per binary orbit than a distant observer, yielding a predicted frequency for reprocessed light:

$$\omega_{\rm repro} = \omega_{\rm spin} - \Omega_{\rm orb}. \qquad (2)$$

I will call this the "orbital sideband." In the CV literature it is sometimes also called the "beat frequency," but I shall avoid this term since it has a well-defined and quite different meaning in acoustics and music (a low frequency which is the difference between two high frequencies).

Why are hard X-rays expected? Close to the white dwarf, the field is assumed to be strong enough to steer accreting gas (assumed to be ionized; neutrals do not care about the field) along field lines to the magnetic poles. The velocity of radial infall is very high, 3000–10,000 km s^{-1}, compared with a sonic speed in the gas that does not exceed $\sim$100 km s^{-1}. A shock therefore develops above the star, and the infalling gas releases its energy in the shock, as depicted in the lower part of Fig. 1. The total energy available is $\sim$150 keV nucleon^{-1}; in principle a strong shock should have $kT_{br}=(3/8)\ E_{\rm total}\approx 60$ keV (Hoshi 1973), but most of the energy is released near the bottom where the temperatures are lower.

As we shall see, this simple theory meets only with mixed success in confronting observations of the energy budget of real systems. In particular, there are plentiful signs that in real stars, most of the energy manages to avoid the shock and burrow into the white dwarf directly. That is why the white dwarf in Fig. 1 has been equipped with an Army helmet.

2.2 The Cast: Rules of the Audition

The basic criterion for membership in this class is the presence of a rapid, highly coherent periodicity in a CV's light curve, typically at optical or X-ray wavelengths. "Rapid" is not essential; the key idea is that $P<P_{\rm orb}$, although most stars have $P\ll P_{\rm orb}$. Stability in period and phase on very long time scales is essential, in order to distinguish the signals from the vastly more common phenomena of quasiperiodic oscillations and flickering.

Having defined the class in this simple manner, we find that the members share distinctive properties which increase our insight into the nature of the class. The following properties are extensively shared among the obvious members, and therefore are significant clues to a star's identity as a DQ Her star:

(a) a stable optical period with $P<P_{\rm orb}$, and usually $P\ll P_{\rm orb}$;
(b) X-ray pulsations at the same, or very similar, period;
(c) pulsations in the He II emission lines, which almost certainly arise from photoionization by the central X-ray source;
(d) circular polarization;
(e) the existence of "sideband periods" in optical and X-ray light, usually on the low-frequency side of the main signal; and
(f) a very hard X-ray spectrum, often with a strong signature of low-energy absorption.

No individual star has all of these traits. But they are either widely shared, or strongly motivated by theory [in the case of (d)]. Some are certainly more important than others—especially (b) and (d), which would establish membership even with no other points in common.

Finally, I should concede that the theorist's definition of a DQ Her star is in principle superior: "a star that looks like Fig. 1." I just wanted to emphasize the empirical clues that actually lead us to make our imperfect classifications in the real world, since we are not permitted telescopic views as sharp as Fig. 1, nor to sprinkle iron filings near the star.

2.3 Roster of the Cast

In Table 1 I present empirical data on definite and very likely DQ Her stars. Column (3) gives the spin period in seconds, and the presence of a first harmonic is indicated by "1H"; this may signify a two-pole accretor, although other interpretations are possible. The presence of another stable period, a lower orbital sideband, is also noted by

TABLE 1
The DQ Herculis Stars

(1) Star	(2) α, δ (2000)	(3) $P_{\rm spin}$ (s)	(4) $\Delta B_{\rm osc}$ (mag)	(5) $\dot{P}_{\rm spin}$ (10^{-11})	(6) $P_{\rm orb}$ (hr)	(7) V	(8) d (pc)	(9) log $\dot{M}$ (g s^{-1})	(10) F_x (2–10 keV) (10^{-11} erg $cm^{-2} s^{-1}$)	(11) $kT_{\rm brems}$ (keV)	(12) log $N_{\rm H}$ (cm^{-2})	(13) References
AE Aqr	$20^h40^m09^s.07$ −00 52 16.3	33.0767335(9) P,X; 1H	0.005	< 0.004	9.87973(1) S,P	11–14	90	16.1	0.3	1.0	20.3	1,2,3,4,5,6
V533 Her	18 14 20.34 41 51 21.3	63.633032(2) P	0.007	< 0.04	~ 5.0 S	14–16	1000	17.6	< 0.05			7,8
DQ Her	18 07 30.17 45 51 31.9	71.06540(1) P,S	0.015	−0.05	4.646909(3) P,S	14.5–15	420	17.9	< 0.05	< 0.7	20.4	9,10,11
H0253+193	02 56 7.9 19 26 38	206.30(4) X	< 0.09		6.0648(5) X,P	> 23	200	16.5	2.6	12–25	23.0	12,13,14
GK Per	03 31 11.82 43 54 16.8	351.341(2) X,P; 1H	0.012	−2.7	47.9233(2) S	10–14	490	17.8– 19.0	4 (Q) 40 (O)	25–42 > 40	22.0 23.2	2,15,16,17, 18,19,20
YY Dra 2A 1150+72	11 43 38.51 71 41 19.2	529.22(8) P,X;LSB,1H	0.020	< 21	3.96(1) S	11–17	155	15.1– 17.0	2.8 (Q)	> 4	< 20.3	21,22,23, 24
V471 Tau	03 50 24.5 17 14 48.1	554.635(2) X,P;LSB,1H	0.008		12.508397(2) S,P,X	13.6	45		< 0.05		18.7	25,26,27, 28
V1223 Sgr 4U 1849–31	18 55 2.32 −31 09 49.3	745.506(1) P,X,S;LSB	0.034	+2.3	3.36586(1) S,P	13–17	400	16.0– 17.9	6.0 (O)	> 5	22.0	29,30,31, 32,33
AO Psc H2252–035	22 55 18.01 −03 10 41.3	805.203(1) P,X,S; LSB	0.041	−6.0	3.59105(4) S,P,X	13–14	250	17.0	4.8	> 20	22.6	34,35,36, 37,38,39
RE 0751+144	07 51 17.3 14 44 23	833.72(2) P,X;SH?	0.026		~ 5.6 S	14.5	400	17.1	4	> 10		40,41

TABLE 1
(Continued)

(1) Star	(2) α,δ (2000)	(3) $P_{\rm spin}$ (s)	(4) $\Delta B_{\rm osc}$ (mag)	(5) $\dot{P}_{\rm spin}$ (10^{-11})	(6) $P_{\rm orb}$ (hr)	(7) V	(8) d (pc)	(9) $\log \dot{M}$ (g s^{-1})	(10) F_x (2–10 keV) (10^{-11} erg $cm^{-2}s^{-1}$)	(11) $kT_{\rm brems}$ (keV)	(12) $\log N_{\rm H}$ (cm^{-2})	(13) References
BG CMi 3A 0729+103	07 31 29.04 09 56 21.8	913.496(1) P,X;SH?,SB?	0.09	−7.0	3.23397(2) S,P,X	14.5–15	500	16.9	2.0	10	22.9	42,43,44 45,46
FO Aqr H2215–086	22 17 55.49 −08 21 5.4	1254.451(1) P,X,S;LSB	0.18	< 2.2	4.84944(3) P,S,X	13.4–14	300	17.1	2.9	> 8	23.3	47,48,49 50,51
TV Col 2A 0526-328	05 29 25.53 −32 49 5.3	1910(4) X	< .01		5.48641(1) S,P	12–14	400	17.3	3.5	> 5	22.5	52,53,54, 55,56,57
TX Col H0542–407	05 43 20.27 −41 01 56.1	1911(10) P,X,S;LSB;1H	0.06		5.718 S	15–16	500	16.8	2.3	> 10	21.3	58,59,60
VZ Pyx H0857–242	08 59 19.95 −24 28 55.7	2918(12) P,X?	0.10		1.78(9) S,P	12–17	250	16.5	2.1	> 5	< 22	61,11
V1062 Tau H0459+246	05 02 27.54 24 45 22.1	3726(36) X,P	0.08		9.95(7) P	16–17	1100	17.7	1.8	20	21.7	61
EX Hya	12 52 24.47 −29 14 57.5	4021.62(1) P,X,S	0.24	−3.5	1.637612(1) S,P,X	10–13	100	15.9– 17	8.0 (Q)	1–10?	20–21?	62,63,64 65,66,67
TW Pic H0534–581	05 34 50.78 −58 01 41.7	7188(5) S,P,X?	0.06		~ 6.2(1) S,P	14–18	500	17.2	2.8 (O)	> 30	< 20.7	68,69,70

TABLE 1
(Continued)

NOTES TO TABLE 1

Pulse period. This may be manifest in optical (P) or X-ray (X) photometry, or spectroscopy (S; the pulsed quantity is usually the first moment of the emission line—the "radial velocity"). Order of labels gives historical order of discovery. Pulses may also show the lower sideband (LSB) or the first harmonic (1H). Number in parentheses is uncertainty in the last digit.

$\Delta B_{\rm osc}$. Semiamplitude of the dominant rapid oscillation in blue light.

$\dot{P}_{\rm spin}$. Upper limits refer to absolute values, i.e., "<3" means $|\dot{P}|<3\times10^{-11}$.

Orbital period. Same comments as for pulses.

Visual magnitude. Accretion light only (classical nova eruptions ignored, and secondary star subtracted).

Distance. For professional stunt astronomers only; do not attempt this at home. See text for discussion.

$\dot{M}$. Time-averaged, unless otherwise specified.

X-ray flux. Average of several measurements, and corrected for low-energy absorption.

Upper limits are derived from nondetections in the 2–4 keV band of the *Einstein* IPC.

X-ray temperature. From an optically thin thermal bremsstrahlung fit, when possible. When authors fit two or more components, I have estimated the best one-component temperature.

NOTES ON INDIVIDUAL STARS

AE Aqr. Transient QPOs ~ 18 s, ~36 s in flares (3). Pulses in UV (5), possibly TeV [Cerenkov radiation; (6)]. Soft X-ray source with F(0.1–4.0 keV) $=7\times10^{-12}$ erg cm^2 s (2).

DQ Her. Soft X-ray source with F(0.1–2.0 keV) $=10^{-13}$ erg cm^2 s (11).

H 0253+193. Accidentally hidden behind the dense core of the dark cloud Lynds 1457, producing $A_V\sim12$ mag (12). Optical properties estimated from *K*-band light curve.

GK Per. Transient QPOs 360–400 s in eruption (18), (19). Different X-ray fluxes in visual quiescence (Q) and outburst (O).

V471 Tau. Visual brightness refers to white dwarf only (most of which is nonaccretion light). X-ray flux also neglects secondary.

V1223 Sgr. Possible 511 KeV emission (Briggs et al. 1991).

RE 0751+144. Periodic variations in circular and linear polarization in *VRI*, suggesting $B_{\rm wd}=8$–18 MG (41). Possible subharmonic at 1667 s.

BG CMi. Circular polarization in *I*, suggesting $B_{\rm wd}\simeq4$ MG. Complex period structure. Dominant signal is 913 s, but spin period is probably 1827 or 1694 s, with harmonics and sidebands (46).

FO Aqr. Rex DQ Stellarum. $\dot{P}$ may oscillate in sign on time scale of a few years; *secular* limit quoted.

TV Col. Additional photometric modulations at 5.19 h and 4.01 days (55,56)—not quite coherent, and origin unknown.

VZ Pyx. Frequent optical outbursts. Optical state unknown at time of X-ray observations.

EX Hya. Complex X-ray spectrum; one component at 0.7 keV, another at 10 keV, possibly others (64), (66).

NOTES TO TABLE 1

(1) Patterson et al. 1980
(2) Eracleous et al. 1991
(3) Patterson 1979a
(4) Welsh et al. 1993
(5) Eracleous et al. 1994
(6) Meintjes et al. 1992
(7) Patterson 1979b
(8) Hutchings 1987
(9) Walker 1956
(10) Patterson et al. 1978
(11) Patterson and Eracleous 1994
(12) Zuckerman et al. 1992
(13) Koyama et al. 1991
(14) Kamata et al. 1991
(15) Watson et al. 1985
(16) Norton et al. 1988
(17) Ishida et al. 1992
(18) Patterson 1991
(19) Mazeh et al. 1985
(20) Crampton et al. 1986
(21) Patterson et al. 1992
(22) Patterson and Szkody 1993
(23) Beuermann and Thomas 1993
(24) Mateo et al. 1991
(25) Jensen et al. 1986
(26) Barstow et al. 1992
(27) Robinson et al. 1988
(28) Clemens et al. 1992
(29) Steiner et al. 1981
(30) Jablonski and Steiner 1987
(31) Warner and Cropper 1984
(32) Osborne et al. 1985
(33) van Amerongen et al. 1987
(34) White and Marshall 1981
(35) Pietsch et al. 1987
(36) Patterson and Price 1981
(37) Hassall et al. 1981
(38) Warner et al. 1981
(39) van der Woerd et al. 1984
(40) Mason et al. 1992
(41) Piirola et al. 1993
(42) McHardy et al. 1984
(43) McHardy et al. 1987
(44) Norton et al. 1992
(45) Augusteijn et al. 1991
(46) Patterson and Thomas 1993
(47) Patterson and Steiner 1983
(48) Chiapetti et al. 1989
(49) Hellier et al. 1989
(50) Hellier et al. 1990
(51) Cook et al. 1984
(52) Hutchings et al. 1981
(53) Motch 1981
(54) Barrett et al. 1988
(55) Hellier 1993a
(56) Augusteijn et al. 1993
(57) Schrijver et al. 1987
(58) Tuohy et al. 1986
(59) Buckley and Tuohy 1989
(60) Buckley and Sullivan 1992
(61) Remillard et al. 1993
(62) Vogt et al. 1980
(63) Jablonski and Busko 1985
(64) Rosen et al. 1988
(65) Hellier et al. 1987
(66) Singh and Swank 1993
(67) Kruszewski et al. 1985
(68) Tuohy et al. 1986
(69) Buckley and Tuohy 1990
(70) Patterson and Moulden 1993

"LSB" (and confusion with the spin period cannot be excluded in all cases). X, P, and S indicate the way in which the period is manifest: respectively, X-ray photometry, optical photometry, and optical spectroscopy. The letter codes are ordered in the historical order of discovery. The number in parentheses denotes the estimated error in the last place, e.g., 805.203(1) s means ±0.001 s. Column (4) gives the measured mean semiamplitude of the optical pulsation in *B* light, after subtracting the secondary's light. Column (5) gives the observed rate of change of pulse period ($\dot{P}$).

Column (6) gives the orbital period in hours, with the same code. Column (7) gives the range in *V* of the accreting component. I have ignored any distractions due to thermonuclear runaways (classical novae), and have subtracted the contribution of the secondary star. Column (8) gives a distance estimate. Where possible, I have based this on an expansion parallax of a nova shell, or the "photometric parallax" of the secondary. These methods seem to give answers good to ~50%. When there is no nova and no detection of the secondary, I use rougher clues from the *K*-band magnitude, upper limits on spectral features of the secondary, interstellar reddening, equivalent widths of emission lines, and Galactic latitude. Column (9) gives an estimate of the accretion rate. Two ingredients go into this: the average $\dot{M}$ appropriate to a star's orbital period (Patterson 1984), and the $\dot{M}$ needed to produce the required M_V from a disk model with a central cavity of radius $R_{\rm mag}$ (with 10% reprocessing of the searchlight luminosity).

Column (10) gives the observed mean X-ray flux in the 2–10 keV passband. This is an average of reported fluxes from *HEAO-1*, *Ariel V*, *EXOSAT*, and *GINGA* (Silber 1992; McHardy et al. 1981; Norton and Watson 1989a; Ishida et al. 1992; and the many papers on individual stars). There is variability but not enough to warrant distinguishing between two states—except for GK Persei, as noted. Columns (11) and (12) give information on the X-ray spectrum. Two notable features are seen: the temperatures are quite high, higher than the ~5 keV typically found for disk-accreting CVs (Eracleous et al. 1991a), and there is enormous low-energy absorption in most stars. The latter is certainly due to cool gas near the X-ray source, probably upstream in the accretion flow; the observed low amount of interstellar reddening proves that it cannot come from interstellar space. The few detailed studies that have been made suggest very complex spectra, with multiple components and/or partial covering of the X-ray source.

Column (13) gives references. Citations include the original paper establishing the nature of the star, and sources of the most useful information on the periodic behavior, not necessarily the most complete or up-to-date papers.

Below I discuss individual stars which I regard as definite, likely, and candidate members. I also discuss several stars which I regard as poor candidates, but which are sometimes included in the class. Of course my judgments are subjective and ever-shifting. Some candidates presently rated poor may still join the list (e.g., from the discovery of X-ray pulses), while some good candidates may have to be expelled for misconduct (e.g., if the periodicity turns out not to be stable in phase).

2.4 The Roll Call: Definite Members

Now we examine details for each of the confirmed and likely DQ Her stars, in order of discovery, but omitting discussions of $\dot{P}$ and energy budgets, which will be done later for the whole class. We use traditional variable-star names, adding the X-ray name when the object was independently found in X-ray surveys. (This is not quite equivalent to being "X-ray selected," since 3 of the stars (AO Piscium, V1223 Sgr, YY Draconis) were previously found in optical surveys, where they languished without attracting much attention.)

2.4.1 DQ Herculis

For 24 years DQ Her remained the only star in its class, which left a lot of time for detailed study. Warner et al. (1972) found an "eclipse-related phase shift," proving that the oscillating light source sweeps *azimuthally* around the accretion disk. Patterson et al. (1978, hereafter referred to as PRN) showed that the oscillation color was identical to the mean color of the star, and that the eclipse-related phase shift begins and ends when the eclipse itself does. This establishes that the oscillating light must be absorbed and reprocessed in the outer parts of the accretion disk, and probably throughout the disk. Chanan et al. (1978, hereafter referred to as CNM) discovered a "wavelength-dependent phase shift" across the He II 4686 emission line. Basically, they found that the 71-s pulse in the middle of the emission line occurs in phase with the continuum pulse, while the pulsation in the red wing of the line occurs slightly earlier, and the pulsation in the blue wing occurs slightly later.

A simple unified model to explain these results was proposed by PRN, CNM, Chester (1979), and Petterson (1980). In brief (borrowing elements from each of these papers), the white dwarf is envisioned to be a 71-s rotator which radiates an EUV/X-ray searchlight beam from its accreting magnetic pole. The geometry is illustrated in Fig. 2. The deep eclipses require a high binary inclination, sufficiently high to create a front/back asymmetry to the accretion disk. In particular, because of the finite opening angle of the disk, the back side presents more surface area to us, and so we see the 71-s pulse maximum when the back side of the disk is irradiated by the searchlight beam. If the He II emission arises from photoionization in the disk, and if the reprocessing is fast ($\ll$71 s), then the red wing of the line should be excited about 18 s before the continuum pulse occurs—in approximate agreement with the results of CNM.

A troubling feature of this model is that the final plunge of accreting gas to the white dwarf surface is expected to produce a strong ($\sim 10^{34}$ erg s^{-1}) hard X-ray component, which is not observed. The observed X-ray flux implies $L_x(0.1\text{–}2.0\ \text{keV}) = 2\times10^{30}$ erg s^{-1}. This discrepancy has led to some serious doubts as to whether DQ Her itself should be properly classified as a DQ Her star!

How can we understand this? It seems likely that the solution lies along one of the following lines:

(1) Petterson (1980) suggested that the nearly edge-on disk actually hides the white dwarf from our direct view. This is geometrically plausible. However, the above-cited evidence (pulsation colors, and both phase shifts) shows that the putative X-ray searchlight beam does illuminate both continuum-forming and line-forming regions of the disk which we *do* see more or less directly. Assuming the disk to intercept about 5% of the white dwarf's luminosity, and assuming an X-ray albedo of 0.3, we still expect to see an X-ray luminosity $\sim 10^{32}$ erg s^{-1}, suggesting still a mild conflict with observation.

(2) The simple theory for DQ Her stars predicts $L_{\rm hx} \gtrsim L_{\rm disk}$, but very few of them actually live up to this expectation. We shall discuss this problem in Secs. 7 and 9, and conclude that the "missing hard X rays" probably emerge in the 0.02–0.2 keV bandpass—unhappily nestled in a very inaccessible regime (due to interstellar and/or circumstellar extinction).

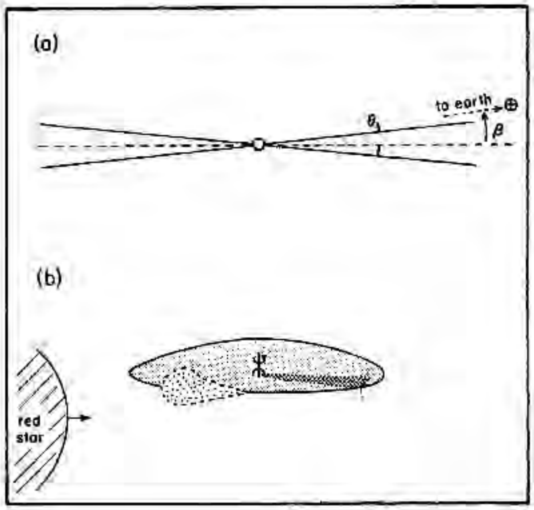

FIG. 2—(a) Earthbound view of DQ Her. The deep eclipses in the light curve prove that the binary inclination is high, so the disk is viewed at a grazing angle. The disk's back side presents more surface area to the observer; and if $\theta > \beta$, then the disk hides the white dwarf completely. (b) Close-up of DQ Her shortly before eclipse. As the white dwarf rotates, its searchlight beam sweeps azimuthally around the disk. As the red star draws across the disk, we see delays in the illumination pattern of the disk. For a one-beam 71-s model, the beam travels through 90° in 18 s—reproducing the eclipse-related phase shift.

It seems likely that *both* of these mechanisms are at work in suppressing the observed X-ray flux. The first reduces the expected flux by a factor of ~ 50 (some contribution from scattering will be hard to suppress), and gets high marks for plausibility since the observed oscillation colors and phase shifts require that the flux is dominated by reprocessing, and that the back side of the disk is more favorably viewed.

The second is strongly supported by a physical argument concerning the origin of the He II 4686 emission line. From Table 1 of CNM, we note that the lines showing a high pulsed fraction are those with high ionization potentials (He II at 54 eV, N III at 47 eV, C III at 48 eV), strongly suggesting that they are powered by a rotating searchlight beam rich in photons of energy > 50 eV. Since the number of recombinations can only equal the number of ionizations, hard X-rays are a relatively inefficient way to produce these lines. For a given luminosity in the beam, the number of ionizing photons is maximized for a blackbody temperature $kT \sim 20$ eV, which would give a blackbody peak at $2.7kT \approx 54$ eV. This is probably too low to be found by any soft X-ray detector yet flown, especially in view of the distance to DQ Her (420 pc, Ferland 1980).

There are some hints that the true spin period might be 142 s. Kemp et al. (1974) reported a 142-s period in the circular polarization; this would normally clinch the matter, but the evidence was fairly weak and has never been confirmed. The high-speed spectroscopy permits either period, but may slightly favor 142 s (CNM, Horne 1993). The photometry could also tolerate either period, but the absence of any 142-s peak in the power spectrum then requires that the two accreting poles (or the two different viewing angles of the same pole) be identical to a very high approximation (Kiplinger and Nather 1975).

2.4.2 AE Aquarii

Patterson (1979a) found strictly periodic 33.08-s variations in this novalike variable, with comparable power in the first harmonic. The upper frame of Fig. 3 shows the average power spectrum in quiescence, illustrating the 33- and 16.5-s signals. During flares, which occur at intervals of ~ 1 hr, the star sports quasiperiodic oscillations (QPOs) on the low-frequency side of the periodic signals. The average power spectrum of AE Aqr in the flaring state is shown in the lower frame of Fig. 3.

Shortly after the discovery of the optical signal, *Einstein* observations showed a 0.1–4.0 keV signal with the same period and phase (Patterson et al. 1980; Eracleous et al. 1991b). Figure 4 shows the X-ray periodogram near the frequency of interest, proving that $P_x = P_{\rm opt}$ to high precision. The high phase stability of the optical signal, plus the existence of its X-ray counterpart, provided strong evidence for its origin in the rapid rotation of a magnetic white dwarf.

The signal is also seen in the vacuum ultraviolet, where the amplitude is extremely high (~ 0.3 mag, Eracleous et al. 1994). The UV spectrum of the pulsed light was found to include a deep absorption near Lyman α, proving that the light originates from an optically thick environment, which is almost certainly a small heated region of the white dwarf photosphere. This is strongly supportive of the basic geometry shown in the lower frame of Fig. 1.

AE Aqr also appears to be a powerful emitter of pulsed TeV gamma-rays (Meintjes et al. 1992). We shall return to this fascinating possibility in our discussion of nonthermal phenomena in Sec. 14.

2.4.3 EX Hydrae

Analyzing a large set of optical photometry, Vogt et al. (1980) found a stable 67-min period in the light curve of this dwarf nova, and suggested a DQ Her interpretation. This was essentially confirmed when a long observation by the *Einstein* IPC revealed strong X-ray pulsations (Kruszewski et al. 1981). Many subsequent X-ray observations have made this star a good test case for detailed theories of the origin of the X-ray modulation; we shall return to this subject in Sec. 7.

2.4.4 AO Piscium (H 2252−035)

Griffiths et al. (1980) identified this X-ray source with a 13th mag cataclysmic variable, subsequently named AO Piscium. In July 1980, 859-s coherent pulsations were found in the light curve, along with a 3.6-hr modulation presumed to be the binary period (Patterson and Price 1981). Subsequent analysis of a pointed observation revealed a period in 2–10 keV X-rays, but at 805 s (White and Marshall 1981). The early papers established the basic model for the system: a magnetic, radially accreting white dwarf rotating every 805 s, illuminating structures fixed in the reference frame of the binary with the "synodic" period

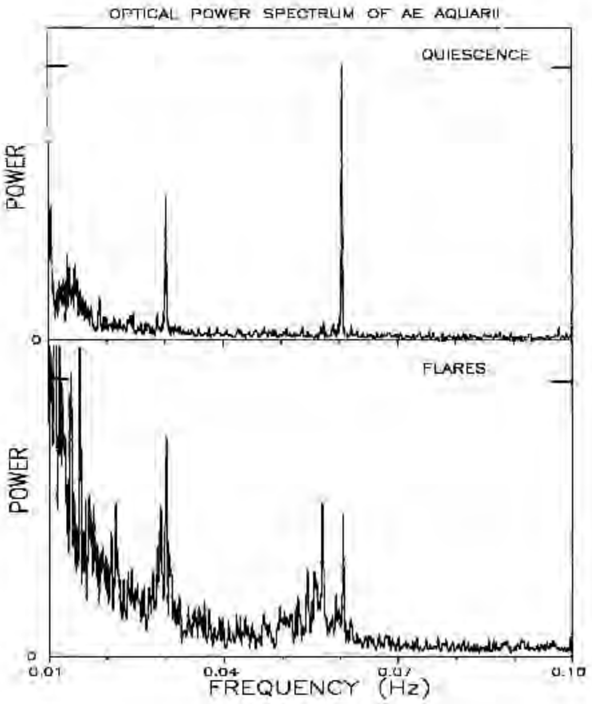

FIG. 3—*Upper frame*: average power spectrum of AE Aqr in quiescence, showing stable signals at 33.08 and 16.54 s. *Lower frame*: average power spectrum in flares, showing QPOs in the low-frequency wings of the periodic signals. The horizontal tick marks indicate the power in a periodicity of semiamplitude 0.002 mag.

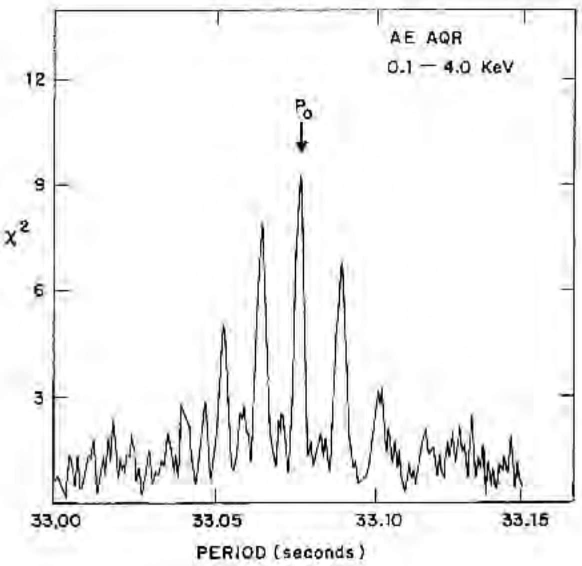

FIG. 4—Periodogram of the soft X-ray (0.1–4.0 keV) light curve of AE Aqr during 1980 May 13–15. Photon arrival times have been corrected for delays introduced in the binary and in the solar system. The central peak occurs at the optical period, within measurement error; the flanking peaks are aliases introduced by 24-hr gaps in the data.

of 859 s (White and Marshall 1981; Hassall et al. 1981; Patterson and Price 1981; Warner et al. 1981). High-speed multicolor photometry has shown that the 805-s pulse dominates at ultraviolet as well as X-ray wavelengths (van der Woerd et al. 1984).

2.4.5 V1223 Sagittarii (4U 1849−31)

Steiner et al. (1981) identified this X-ray source with a known but misclassified star, and found strictly periodic optical pulsations with $P=794$ s, thus essentially proving its membership as a DQ Her star. Subsequent observation with *EXOSAT* revealed the expected X-ray pulsations, but at a period of 745 s, thus making it a virtual twin of AO Psc (Osborne et al. 1985).

2.4.6 BG Canis Minoris (3A 0729+103)

McHardy et al. (1984, 1987) identified this hard X-ray source with a 15th-mag star showing strictly periodic optical and X-ray variations with $P=913$ s. Subsequent observation revealed circular polarization in the infrared, which provides convincing evidence that a strong magnetic field is present (Penning et al. 1986; West et al. 1987). Chanmugam et al. (1990) estimated $B \sim 4$ MG. The optical power spectra show additional peaks at somewhat lower frequency, and a long X-ray observation shows an extra peak at slightly higher frequency (Norton et al. 1992a; Patterson and Thomas 1993). These signals are weak and in need of confirmation, but certainly suggest that the dominant 913-s signal is a harmonic or sideband of the true spin frequency. Patterson and Thomas suggested that all of this somewhat confusing evidence can be reconciled with a two-pole accretor and $P_{\rm spin}=1694$ s. We still list the star at 913 s in Table 1, because that period dominates at all wavelengths explored to date.

2.4.7 FO Aquarii (H 2215−086)

Patterson and Steiner (1983) identified this hard X-ray source with a 13th-mag star showing strictly periodic 20.9-min optical pulsations. Subsequent observation with *EXOSAT* revealed the expected 21 m X-ray pulsations, which essentially resemble the pulsations of other DQ Her stars (Cook et al. 1984; Norton and Watson 1990).

FO Aqr is the unchallenged "king" of the DQ Her stars. Royal light curves are shown in Fig. 5, illustrating the huge amplitude of the 21 m pulses, as well as a broad "orbital dip" which is a characteristic signature of DQ Her stars. Figure 6 shows the average power spectrum of the optical light curve, demonstrating the presence of weak orbital sidebands at $\omega-2\Omega$, $\omega-\Omega$, and possibly $\omega+\Omega$.

2.4.8 GK Persei

This star is famous as one of the century's brightest classical novae, reaching $V=1$ during its 1901 outburst. But in addition to the one classical nova outburst, the star also shows occasional episodes of enhanced luminosity, sometimes characterized as "dwarf-novalike" despite the observed very leisurely time scales for rise and decay (weeks instead of days; see Sabbadin and Bianchini 1983). During a 1983 optical eruption, when the star was at

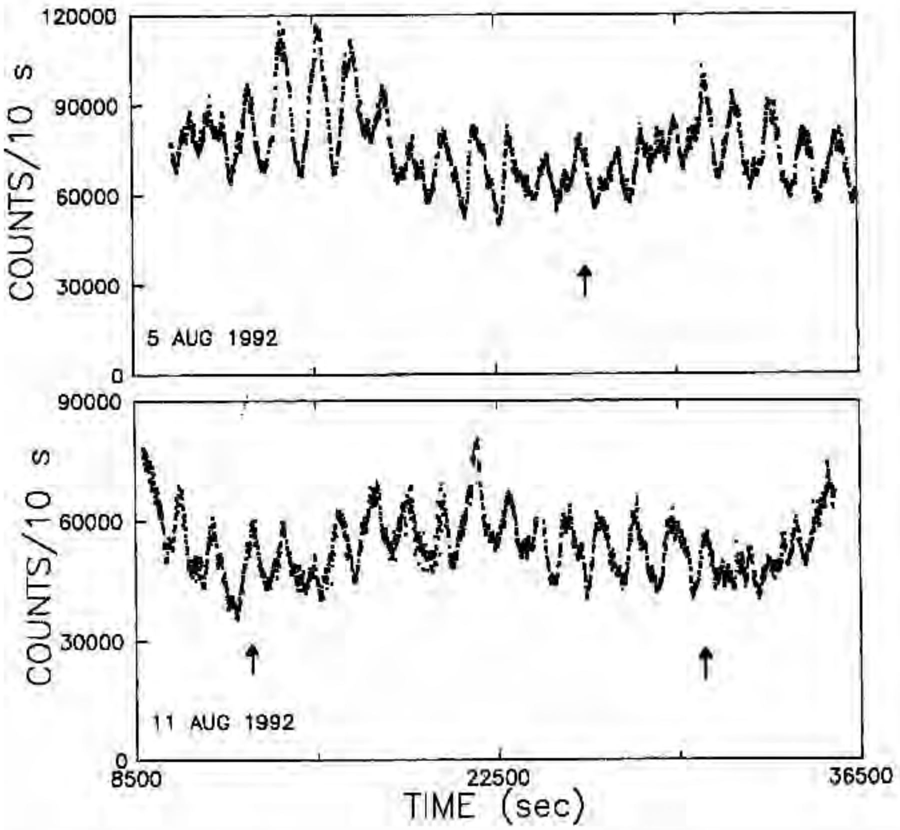

FIG. 5—Light curves of FO Aqr, at 10 s point^{-1}. The arrows indicate the scheduled times of orbital minima.

$V \sim 11$, a long observation by *EXOSAT* revealed a bright hard X-ray source with pulsations at $P=351.34$ s (Watson et al. 1984, hereafter WKO). This established the existence of an accreting magnetic white dwarf in the system. Subsequent study (Norton et al. 1988; Eracleous et al. 1991b) showed the existence of X-ray pulsations also at quiescence, with several marked differences:

(1) a smaller pulsed fraction (~20% compared to ~50% in eruption);

(2) strong evidence for the contribution of two magnetic poles to the X-ray emission; and

(3) no evidence for a soft X-ray component as required in eruption by WKO.

There is an optical counterpart of the 351-s X-ray period, visible in *U* light, as well as QPOs in the low-frequency wing of the primary signal. The various reports of QPOs (Patterson 1981; Mazeh et al. 1985; Patterson 1991) suggest that the QPO period is longer in outburst than in quiescence. This lends some support to the "blob illumination model," in which the observed QPO period arises from the periodic illumination of orbiting blobs in a prograde disk.

2.4.9 TV Columbae (2A 0526−328)

TV Columbae is an X-ray-selected CV which shows a 5.5-hr period in the emission-line radial velocities (interpreted as the orbital period), and photometric periods of 5.5 hr, 5.2 hr, and the beat period of 4.0 days (Hutchings et al. 1981; Motch 1981; Bonnet-Bidaud et al. 1985; Barrett et al. 1988; Augusteijn et al. 1993; Hellier 1993a). The DQ Her membership of the star was established when Schrijver et al. (1987) found coherent X-ray pulsations with a period of 1911 ± 5 s in the 2–8 keV X-ray light curve from an *EXOSAT* observation. With this cornucopia of periods, TV Col has been a popular star with magnetic CV pundits.

The simplest and still viable model is that of Bonnet-Bidaud et al. (1985) and Barrett et al. (1988). In this model, 1911 s and 5.5 hr are, respectively, the spin and orbital periods, and the other two periods arise from the free precession of an accretion disk assumed to be somewhat out of the orbital plane. The disk itself precesses with a 4-day period, which produces a photometric modulation, possibly from the varying visible surface area of the disk. The 5.2-hr period is interpreted as the interval between successive identical alignments of the secondary star with the disk. Because free precession is retrograde (regression of the line of nodes), this should occur with a period slightly *shorter* than the orbital period. The actual physical mechanism for producing the 5.2-hr light variation could be variable shadowing of the secondary by the tilted disk (Bonnet-Bidaud et al. 1985), or a variation in the (angle-averaged) hotspot luminosity due to the varying distance of infall as the accretion stream moves around the tilted disk (Barrett et al. 1988).

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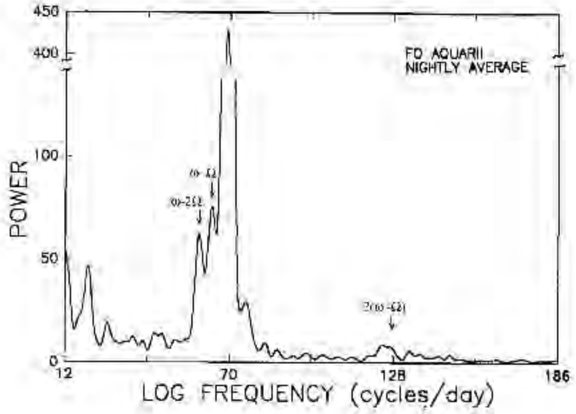

FIG. 6—Power spectrum of FO Aqr, averaged over nine single-night observations. 400 units of power corresponds to a semiamplitude of 0.16 mag. The weak orbital sidebands change in relative strength from night to night.

2.4.10 H 0253+193

Halpern and Patterson (1987) called attention to the positional coincidence (within 5′) of this unidentified X-ray source with the dark core of the nearby molecular cloud Lynds 1457. The nature of the object remained a puzzle until the discovery by *GINGA* of coherent 206-s pulsations in the X-ray light curve (Takano et al. 1989; Koyama et al. 1991); this established that it must be an accreting compact star, presumably rotating with $P=206$ s. Patterson and Halpern (1990) reviewed the available choices and decided that despite the remarkable positional coincidence, the object is probably a background DQ Her star, shining (barely) through ~ 12 mag of visual extinction.

Kamata et al. (1991) discovered abrupt total eclipses of the X-ray source, recurring with a strict period of 6.06 hr. Infrared photometry (Zuckerman et al. 1992) has revealed a $K=13.3$ star acceptably close to the X-ray position, and varying with a period of ~ 3.03 hr. The X-ray eclipse period and phase are fully consistent with the IR data, if the IR wave form is assumed to be "double humped" (i.e., two humps per orbital period). These findings prove that H 0253+193 is an X-ray pulsar in a 6.06-hr binary system, seen sufficiently edge-on to exhibit total eclipses of the compact star, and to show the Roche deformation of the secondary in the infrared light curve.

The faintness of the X-ray source, the high galactic latitude, and the brightness of the infrared counterpart all argue very strongly in favor of an accreting white dwarf rather than a neutron star. Thus, the system is certainly a *bona fide* member of the DQ Her club.

The existence of sharply defined X-ray eclipses permits some constraints to be placed on the X-ray emitting region. The knife edge of the secondary draws across the white dwarf with a relative velocity of ~ 300 km s^{-1}, but the X-ray emission region at the magnetic pole sweeps in the same direction with a speed that ranges from 100 km s^{-1} (if the obliquity between magnetic and rotation axes is large) to near zero (if the obliquity is low). The slight curvature of the secondary's limb also reduces the effective speed of the occulting bar. Adopting $v=200$ km s^{-1} and an observed ingress/egress duration of 75 s, we estimate a diameter of 15,000 km for the emission region—about the diameter of a white dwarf of average mass (0.6–0.7$M_{\odot}$).

This is reasonable evidence that the emission region is not small, as typically seen in AM Her stars, but comparable to the white dwarf itself. Interpreted at face value, this is extremely important because it allows us to understand why the observed wave forms in DQ Her stars are nearly sinusoidal, and perhaps why a pulsed soft X-ray component is never seen (because the energy is deposited over a fairly large area, it re-emerges at too low a T_e to leak significant flux above the threshold of ~ 0.1 keV typical of soft X-ray detectors). This topic will be reexamined in Sec. 7.5.

2.4.11 TX Columbae (H 0542-407)

Tuohy et al. (1986) report X-ray and optical light curves for this star. The *EXOSAT* LE light curve shows convincing evidence for a signal with $P=1920\pm 30$ s, while the optical light curve suggests periods of 2106 and 1054 s (Buckley and Tuohy 1989; Buckley and Sullivan 1992). Published data are too sparse to really prove high coherence, but the X-ray and spectroscopic modulations are enough for me to consider its membership "certain."

2.4.12 YY Draconis (3A 1148+719)

This star displays stable optical and X-ray pulsations at fundamental periods of 529 and 550 s, with the amplitudes and wave forms varying strongly with time and wavelength (Patterson et al. 1992; Patterson and Szkody 1993; Beuermann and Thomas 1993). The true spin period is 529 s; the 550-s signal is the low-frequency orbital sideband. The white dwarf is probably a two-pole accretor, since the dominant signals are generally at 265/275 s.

2.4.13 RE 0751+144

This newly discovered CV was found as a source of very soft X-rays (70–140 A) by the *ROSAT* wide-field camera, and a 13.9-min period was subsequently detected across many wavelengths (V band, K band, 2–10 keV X-rays; Mason et al. 1992). Piirola et al. (1993) found variable circular and linear polarization, predominantly in R and I light, recurring with the 13.9-min period. The circularly polarized light is consistent with cyclotron radiation originating in a region with $B=8$–18 MG.

This star seems to have everything, and is likely to become the best-studied DQ Her star. At present, there is still some doubt about its period. The photometric data of Piirola et al. showed a strong even–odd effect, suggesting that it may be a two-pole accretor with $P_{\rm spin}=27.8$ min. But that would make the polarization curve more difficult to understand. This can probably be resolved by a careful measurement of the sideband pulse; for the estimated 5.6-hr orbital period, a one-pole accretor implies a side-

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band period of 14.5 m, and a two-pole accretor implies 15.15 m.

2.5 The Roll Call: Likely Members

Now we discuss a few candidate DQ Her stars where the credentials are strong but not quite conclusive.

2.5.1 V533 Herculis

Photometry of this old nova revealed a very stable 63-s periodicity in the light curve, with an amplitude varying erratically in the range 0.001–0.015 mag (Patterson 1979b). Robinson and Nather (1983) reported that the periodic signal vanished in 1981, and argued that this behavior is inconsistent with an origin in a magnetic rotator.

I have been accumulating high-speed photometry of this star intermittently since 1977. During 1977–1980, the star displayed a 63-s signal, and observations were sufficiently densely spaced and well distributed to yield a unique ephemeris:

Pulse maximum

$$=JED_{\odot}\ \underset{(3)}{2{,}443{,}283.83167}+\underset{(2)}{0.00073649343}E \qquad (3)$$

Figure 7 is an O-C diagram of these 4 yr of pulse timings with respect to a constant-period ephemeris. The linear fit indicates $|\dot{P}|<4\times10^{-13}$.

The basic argument for including V533 Her in the roster is simply the presence of a very rapid signal demonstrably stable in period and phase over an interval of years. There are essentially two arguments against it:

(1) *The absence of pulsed X-rays.* This is a problem, but it seems to be one which all the rapid rotators share. We will see below that the upper limit puts the star basically in the same status as AE Aqr and DQ Her.

(2) *The disappearance of the signal* in photometry obtained since 1981. This seems to me a weaker argument. In general, accretion-related phenomena are renowned for their variability, and changes in pulse amplitude are not unusual. More specifically, in 1981 V533 Her entered a minioutburst state in which it rose to $B=14.4$ from a quiescent magnitude of 15.7. This state persisted at least through 1989. Thus the accretion rate through the disk may have increased by a factor of ~4. Although the mechanism is unknown, there are substantial empirical clues in well-certified DQ Hers that brightening episodes can somehow suppress the optical periodicity.

2.5.2 V471 Tauri

This 9th-mag eclipsing binary is not strictly a cataclysmic variable, since the secondary does not fill the Roche lobe, and signatures of mass transfer are subtle at best. The *EXOSAT* observations reported by Jensen et al. (1986) showed a soft X-ray pulsation with $P=555$ s, and Robinson et al. (1988) discovered a U-band signal at the same period. Jensen et al. suggested that a likely mechanism for the modulation is "accretion dark spots" on a rotating white dwarf, caused by the extra soft X-ray opacity added by freshly accreted matter of solar composition.

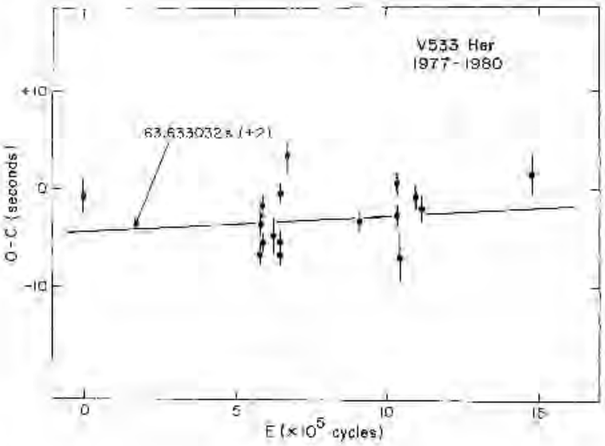

FIG. 7—O-C diagram of V533 Her's 63-s pulse during 1977–80. The linear fit indicates an unchanging period.

A new piece of evidence strongly favors a rotation model for the periodicity. More sensitive photometric observations have revealed the low-frequency orbital sideband (Clemens et al. 1992), arising from reprocessing in the secondary. Comparison of the phases of direct and reprocessed optical signals, as well as a simple measurement of the *ROSAT* pulse (Barstow et al. 1992), shows that the white dwarf's optical and X-ray pulses are 180° out of phase. This agrees with the idea (one of them, anyway) suggested by Jensen et al.: the soft X-ray opacity produces X-ray dark spots, and the dammed-up radiation emerges instead in the optical.

2.5.3 V1062 Tauri (H 0459+246)

This X-ray-selected star has an orbital period of 9.9 hr, and an X-ray signal with $P=62$ min and a pulsed fraction exceeding ~60% (Remillard et al. 1993). The latter is normally a reliable indicator of magnetically channeled accretion; I label the star as only "likely" because the available data are still too sparse to prove the stability of the pulsation beyond doubt.

2.5.4 TW Pictoris (H 0534−581)

This high-excitation CV was identified with a *HEAO-1* X-ray source by Tuohy et al. (1986). Buckley and Tuohy (1990) reported periods of 6.5±1.0 hr and 2.1±0.1 hr in the radial velocities, which they regarded as evidence of the star's DQ Her membership. This is consistent with the photometry, which seems to reveal periodicities at ~6.1 hr and 119.8 min (Patterson and Moulden 1993).

This is a likely DQ Her star, but close examination of the detected periodicities leaves some doubt: about the stability of the signals, about the possibility that the candidate "spin frequency" is simply the 2nd harmonic of the orbital frequency, and about the night-to-night cycle counts. Measurement of a precise spectroscopic period would probably resolve this matter.

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2.5.5 VZ Pyxidis (H 0857−242)

Like EX Hydrae, this star has a short orbital period, and a putative spin period which is quite long (~ 50 min) and primarily observable in the faint state (Remillard et al. 1993). Precise values for these periods are not yet known, and therefore stability is not proven. But the existence of a probable X-ray signal at ~ 50 min (Patterson and Eracleous 1994) makes the star a likely candidate.

2.6 Other Candidates

Now I turn to a few stars which show signs of membership, but not quite enough for me to consider membership "likely." These stars are particularly attractive candidates for further study. Apart from clarifying the census, they should enable a deeper understanding of the diversity (or uniformity!) of behavior accessible to DQ Her stars.

2.6.1 WZ Sagittae

A very coherent 27.87-s periodicity was discovered in the optical light curve of this dwarf nova by Robinson et al. (1978). The amplitude was highly variable but averaged ~ 0.006 mag. Because a second period at 28.97 s was found to be present on two nights in 1971, Robinson et al. favored white dwarf pulsation over rotation as the origin of the periodicity. Patterson (1980) found that during a long series of observations in 1976–78, there were several weak signals present on the low-frequency side of the principal 27.87-s signal. These are shown in Fig. 8. He suggested that the magnetic rotator hypothesis might still be saved, by interpreting the weaker signals as not independent pulsations, but "sideband" signals arising from reprocessing in blobs in the accretion disk.

Ever since the dwarf nova eruption of WZ Sagittae in December 1978, the properties of the periodicity have dramatically changed. Observations during the eruption showed no trace of the signal, to typical limits of <0.001 mag. By 1979 May, the star had faded to $V\sim 14.5$, about 1 mag above quiescence. The stable 27.87-s period of the previous year had disappeared, and in its place was a somewhat weaker signal at ~ 29 s. Unfortunately, the night-to-night coherence of the latter signal has not been established with certainty.

I have continued to monitor WZ Sge since then, and have noticed that the star remains slightly brighter than the preoutburst state ($V\sim 14.9$ vs. 15.5), with no clear evidence of periodicities. Typical upper limits for pulsations are only slightly lower than the principal pulse detected during 1976–78, but a few are much lower.

Besides the optical periodicity seen during 1976–78, there are basically no other hints to suggest a DQ Her identification. The spectrum in quiescence has a fairly low excitation, with He II weak or absent. Eracleous et al. (1991b) found no X-ray pulsations present in the *Einstein* observations, for any of the periods of interest. In the longest X-ray observation, the search extended down to a pulse fraction of $\sim 8\%$.

WZ Sge is a possible DQ Her star, but new confirming evidence is needed; the discovery of a stable X-ray period, or the return of the 1976–8 period, would be important steps in this direction.

2.6.2 TT Arietis

This star has an orbital period of 3.30 hr, and a photometric period of 3.19 hr which is probably some sort of "superhump" phenomenon (Udalski 1988). It also has large-amplitude quasiperiodic oscillations with $P\sim 20$ m (see light curve in Fig. 9). The signals are of extremely low coherence, wandering in phase on time scales of a few cycles at most. Nevertheless, they are considerably reminiscent of the QPOs flashed by AE Aqr and GK Per when bright. Thus it is a reasonable speculation that an underlying stable period may be present, but masked by some unknown physical process which accompanies the high-$\dot{M}$ state.

Searches for a stable period in UV and X-ray light would be of great interest. It is also possible that a *weak* stable signal is lurking in the glare of the optical QPO. Thomas et al. (1994) report an optical period of 1168 ± 2 s in one extensive data set, but its long-term stability is unknown.

2.6.3 H 0551−819

The light curve of this star is essentially indistinguishable from that of TT Ari, with a prominent hump at 3.0 hr and QPOs in the range $P=16$–25 m (Silber 1992; Buckley et al. 1993). The high value of F_x/F_v, the strength of the He II emission, and the resemblance to the QPOs in GK Per and AE Aqr make a DQ Her hypothesis attractive.

2.6.4 V795 Herculis

This star is another sibling of TT Ari. A large-amplitude 2.8-hr photometric hump was present during 1983–89, leading many authors to classify it as a DQ Her star since the signal was fairly stable and satisfied the condition $P\neq P_{\rm orb}=2.6$ hr (Shafter et al. 1990; Zhang et al. 1991). To me this interpretation does far too much violence to other assorted pieces of empirical and theoretical wisdom about radial accretion, synchronism, and X-ray emission (see Sec. 2.7.6); the signal is more likely to be a "superhump." On the other hand, I think the white dwarf may well be a magnetic accretor, because of a QPO persistently present at 19 m (Patterson and Skillman 1994), and because of the large-amplitude streaming motions at $P_{\rm orb}$ discovered by Haswell et al. (1994).

2.7 Poor Candidates

Finally, there are stars which have appeared for the audition but have met very few of the selection criteria. Until further evidence emerges, these should not be assigned to the DQ Her class.

2.7.1 SW Ursae Majoris

This star was proposed as a DQ Her star by Shafter et al. (1986), based primarily on a detection of a 15.9-min period in a 2-hr optical light curve at quiescence in 1984

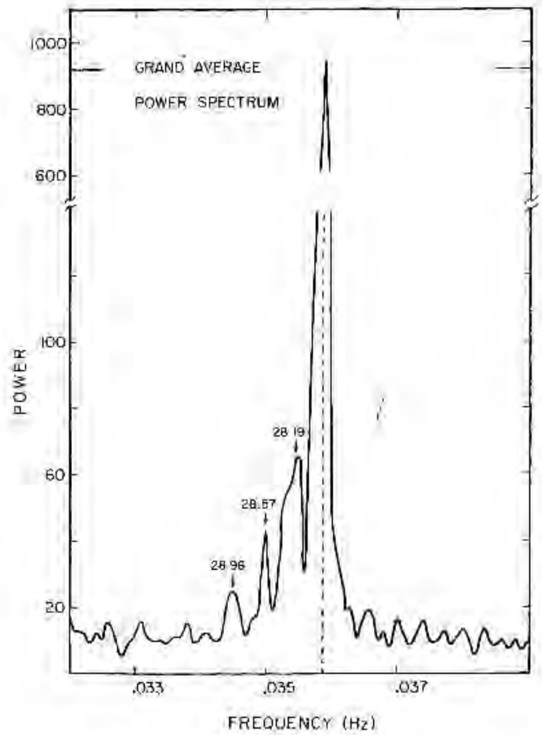

FIG. 8—Average power spectrum of WZ Sge during 1977–78. In addition to the main pulse at 27.8684 s, there are also weak sideband signals, which are labeled with their periods in seconds. 900 units of power indicate a signal semiamplitude of 0.008 mag.

March. Extensive photometry by Robinson et al. (1987) in 1986 March did not confirm this period (with the star in a much higher luminosity state). We observed this star at quiescence ($V\sim17$) on four nights in 1989–90, and failed to find any evidence of the short period. In Fig. 10 we show the average amplitude spectrum obtained during two long observations on consecutive nights in 1990 January. The arrow points to the candidate frequency. The upper limit to a signal at this frequency is $\sim$0.01 mag, about a factor of 8 below the amplitude reported in the 1984 observation.

This establishes that the signal is *transient*, even at quiescence. Perhaps more importantly, no strong claim can be made for the coherence of the signal at any time, since the 1984 observation only spanned $\sim$10 cycles. It is certainly common enough for cataclysmic variables to display short-lived oscillations of low coherence in their light curve; these could mimic a stable period during a brief observation.

Is there any other evidence on this point? A periodic signal in X-rays would be a strong indicator, and Shafter et al. (1986) present *EXOSAT* soft X-ray light curves, folded with a 15.9-min period, which appear to show a modulation with a pulsed fraction of $\sim$40%. However, this detection is not very persuasive. It is again too brief to establish the coherence of the signal. And it is difficult to judge the significance of the detection without a power spectrum, periodogram, or some other "unbiased" method of periodicity search.

All things considered, it seems that SW UMa's credentials as a DQ Her star must be considered doubtful at best, and we have demoted the star accordingly.

2.7.2 V426 Ophiuchi

Periods of $\sim$60 and $\sim$30 min have been reported in the X-ray and optical light curves of this novalike variable (Szkody 1986; Szkody et al. 1990), and as a result the star is frequently listed as a DQ Her type. But Hellier et al. (1990b) found no signature of either period in the emission lines, in an independent set of optical photometry, or in a reanalysis of the *EXOSAT* X-ray data. The credentials of this star must be considered weak.

2.7.3 KO Velorum (E 1013-477)

In a search for counterparts of *HEAO-1* X-ray sources, Mason et al. (1983) found this star in an *Einstein* IPC field, and suggested, on the basis of a spectrum showing high-excitation emission lines, that it might be an AM Her star. Subsequent polarimetry (Cropper 1986) did not support this. A grand total of seven photometric periods, ranging from 1.1 to 10.1 hr, have been suggested by various authors, and variously ascribed to an orbital or spin origin (reviewed by Mukai and Corbet 1991; Sambruna et al. 1992). But essentially none of these periods are convincing. The only real motivation for considering this star to have even weak credentials is the F_x/F_v ratio, which would be high if the star is indeed the *HEAO-1* source. However, there is no way to know this; the *Einstein* IPC observation gave $F_x/F_v=0.3$, quite normal for a low-$\dot{M}$ CV, and it is possible that the star is fortuitously in the large *HEAO-1* error box. Continued optical photometry, and a sensitive observation in soft X rays, may vault this star back onto the list, but at present it is not a good candidate.

2.7.4 V603 Aquilae

Evidence for a 61.4-min signal in the visual, ultraviolet, and X-ray light curves has been presented (Udalski and Schwarzenberg-Czerny 1989; Schwarzenberg-Czerny et al. 1992), and disputed (Eracleous et al. 1991b; Patterson et al. 1993). Additional observations, especially in the UV where the amplitude is reported to be high, are needed to settle this.

2.7.5 AH Eridani

A limited amount of photometry suggested a period of $\sim$42 min in this dwarf nova (Howell and Szkody 1988; Szkody et al. 1989). This could represent a spin period, or it could be simply the first harmonic of a 84-min orbital period. It is also possible that the variations are not strictly periodic; the published coverage of $\sim$10 hr is still too sparse to prove stability.

2.7.6 Miscellaneous Stars with $P\approx P_{orb}$

Some CVs display periods displaced by a few percent from $P_{\rm orb}$. Two of these (V1500 Cygni and BY Camelopardalis) show periods in the circular polarization displaced

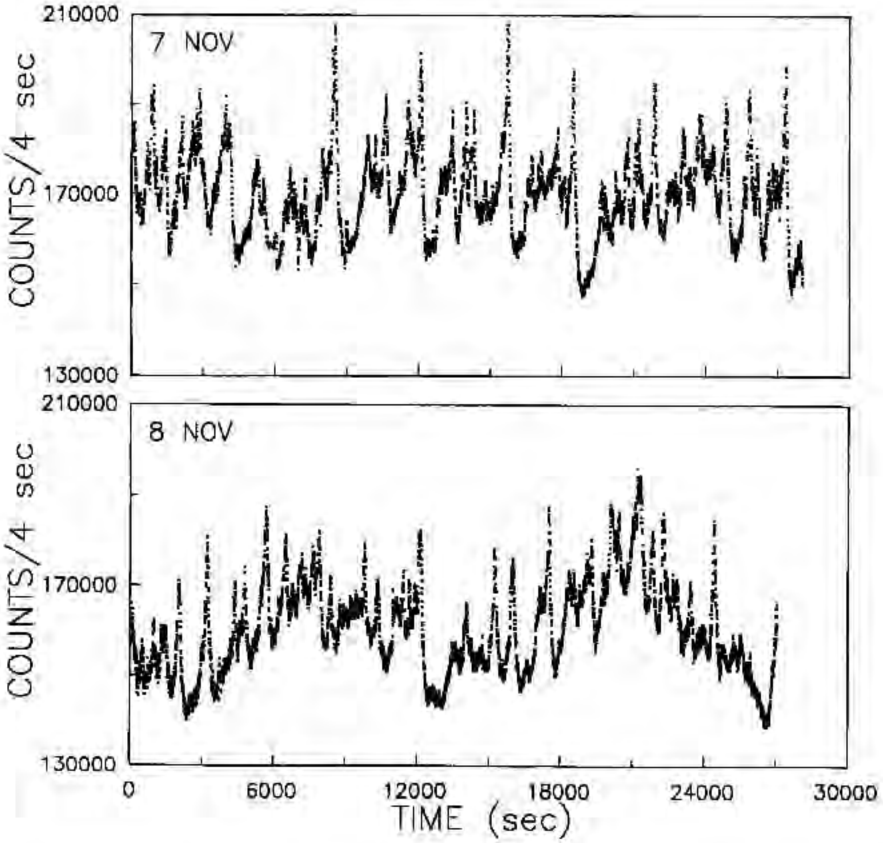

FIG. 9—Light curves of TT Ari, a *candidate* DQ Her star. The rapid flickering has a time scale of ~20 m and an amplitude ~0.1 mag, but no stable signal is detected to a semiamplitude upper limit of 0.008 mag.

by $<2\%$; these are thought to be AM Her stars which have temporarily lost synchronism. The other stars (reviewed by Patterson et al. 1993) show *photometric* periods which are likely to represent "superhump" phenomena of some kind. I consider it unlikely that any of these stars are proper members of the DQ Her class—at least not at periods near $P_{\rm orb}$. Examples are AM Canum Venaticorum, PG 0917+342, CP Puppis, and V795 Herculis. The arguments vary slightly from star to star, but they run like this: the observed phase stability of the signal is generally somewhat poor, the stars fail to show incipient AM Her characteristics, and it is difficult to understand how the stars could remain in nearly synchronous rotation for long. The latter is especially perplexing if the photometric period slightly *exceeds* $P_{\rm orb}$, which is true for most of these stars.

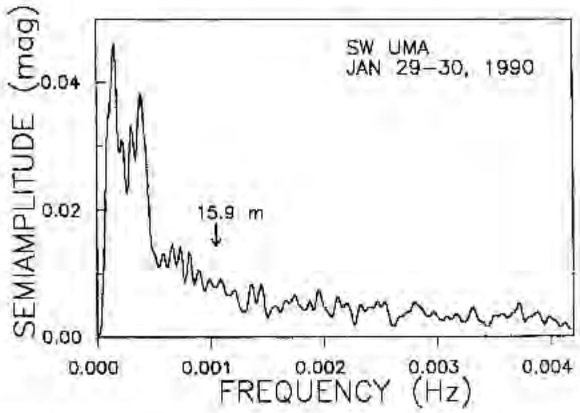

FIG. 10—Average amplitude spectrum of SW UMa on two consecutive nights in quiescence. The arrow points to the location of the reported 15.9 m period.

2.8 Others

About another dozen stars have been proposed as members, on miscellaneous grounds: strong He II, high F_x/F_V, lack of dwarf nova eruptions, lack of polarization, "appearance" of the flickering. Sometimes this is justified by choosing for comparison one particular star of another type, e.g., U Geminorum, and then citing some difference to rule out membership in that class (e.g., dwarf novae). But cataclysmic variables of each type simply show *too large a dispersion* in these secondary properties to use them for classification; the *defining* criteria should be used. In our case, until that powerful telescope comes along which reveals views like Fig. 1, the detection of a stable period is the *sine qua non.*

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3. ORBITAL SIDEBANDS

Many DQ Hers show periodic signals at the orbital sideband of the spin frequency. If ω is the spin frequency and Ω is the orbital frequency, then it is very common for an optical signal at $\omega-\Omega$ to appear. First recognized in AO Psc, this is the sidereal/synodic effect, arising from the reprocessing of the white dwarf's pulsed flux in a structure moving around with the binary period. But amplitude modulations can also create signals at $\omega-2\Omega$ and $\omega+\Omega$, and do (Warner 1986). Additional complications can arise, even in the X-ray pulse, depending on binary inclination, magnetic obliquity, and the possible existence of a second accreting pole (Wynn and King 1992).

The $2\omega-\Omega$ pulse is particularly interesting since it is a plausible consequence of "diskless accretion," but hard to produce in disk accretion (Wynn and King 1992). Hellier (1992) studied the *EXOSAT* archive and found no convincing examples of such pulses, under the assumption that the dominant signal really does give the true spin frequency. Patterson and Thomas (1993), attempting to account for the very complex power spectrum of BG CMi, found that the one hypothesis which "explained" all five peaks in the power spectrum had the feature that the dominant 913-s signal was the $2\omega-\Omega$ pulse. The $\omega-\Omega$ pulse, if strong in X rays, is another signature of diskless accretion; TX Col appears to be an example of this (Buckley and Tuohy 1989; Hellier 1991). But since the detailed power spectra tend to be somewhat unstable in all of these stars, it is difficult to say whether this type of reasoning is astrophysics, or recreational mathematics!

4. A $P_{\rm spin}-P_{\rm orb}$ RELATION?

Some observers have noted a correlation between the spin and orbital periods in DQ Her stars, roughly $P_{\rm spin}=0.1\ P_{\rm orb}$ (Barrett et al. 1988; Warner and Wickramasinghe 1991). And some theorists have considered this relation sufficiently credible to seize upon it as a clue to the structure and evolution of magnetic CVs (Wickramasinghe et al. 1991; King and Lasota 1991).

This would indeed be an interesting clue if it were true, but it is not. In Fig. 11 we show a plot of $P_{\rm spin}$ vs. $P_{\rm orb}$. The lower line represents the alleged relationship, which bears little resemblance to the data. The contrary conclusion was reached by using poorly selected lists of DQ Her stars—excluding obvious members, and including very probable nonmembers. This is just a relationship that did not work out; theorists would do themselves a favor by forgetting about it.

5. A PERIOD–AMPLITUDE RELATION

5.1 The Empirical Relation

There is another relation among DQ Hers, not remarked on in print but with the advantage that it is actually true. This is the correlation of optical pulse amplitude with spin period, shown in Fig. 12. Here I have measured (and listed in Table 1) the *mean semiamplitude of the dominant optical pulsation in blue light*, after subtracting the light from the secondary. I have used an orbital average to minimize flickering and to remove possible interference from sidebands.

Most commonly, the data consist of white-light photometry with blue-sensitive photomultiplier tubes; this is effectively similar to a B bandpass, unless there is a complication in the energy distribution (Balmer jump in emission, bright secondary star). Sometimes the available data is in U or V light. In all cases I have reduced the data to an estimated pulse semiamplitude in B light (which is a good measure of the local continuum).

Several stars (AE Aqr, V533 Her, GK Per) occasionally go into "high states," where the pulse amplitude is much reduced, for reasons not understood. I have used the data for the "normal state."

The general trend is that the amplitudes increase with $P_{\rm spin}$, according to

$$A=0.06\ \text{mag}\ P_{1000}^{0.65\pm0.10}, \tag{4}$$

where $P_{1000}=(P_{\rm spin}/1000\ \text{s})$. What is the reason for this?

5.2 A Selection Effect?

One possibility is that it is entirely a selection effect. Coherent signals of ~0.01 mag are easy to detect if the period is short, but very difficult if the period is long. The boundary between white and shaded regions in Fig. 12 represents my estimate of the detection threshold for a periodic signal in a typical 5-hr observation, assuming favorable weather and adequate counting statistics.[1] The slope of the line is similar to that of the empirical correlation. Is that the explanation?

Well, probably not. It is true that many long-period systems could live in the shaded region, unknown to us. But there is certainly no selection effect forbidding the discovery of large-amplitude, short-period systems. Failing to imagine how they could hide from us, we should probably concede that they do not exist. It seems very likely that the correlation is genuine.

5.3 An Exotic Form of Kepler's 3rd Law?

This proportionality can be derived in a simple way. The luminosity released in the final radial infall to the white dwarf is very nearly

$$L=GM_{\rm wd}\dot{M}/R_{\rm wd} \tag{5}$$

and in our idealized world all of it is pulsed. (In practice this depends on binary inclination, magnetic obliquity, and the size of the emission region.) But only a small fraction ϵ of this appears at visual wavelengths, so the pulsed optical luminosity is

$$L_{\rm pulsed}=\epsilon GM_{\rm wd}\dot{M}/R_{\rm wd}. \tag{6}$$

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[1] Of course, this does not imply that a signal can thereby be certified as strictly periodic! The meaning of the threshold is that a signal above the line is likely to stand above the noise sufficiently to attract attention and warrant further study, which is the relevant point here.

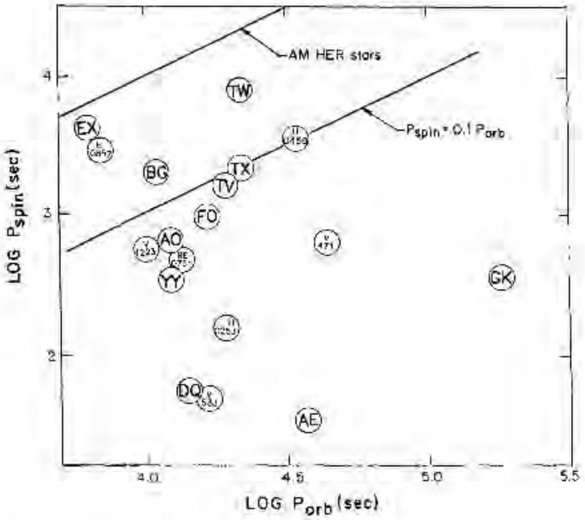

FIG. 11—P_{spin} vs. P_{orb} for DQ Her stars, with stars identified on a first-name basis. The points clearly lie in a plane, but pay little attention to the "$P_{spin}=0.1P_{orb}$" relation.

We assume that the unpulsed light comes from the accretion disk, which emits primarily in the optical. This luminosity is

$$L_{steady}=GM_{wd}\dot{M}/R_{mag}, \qquad (7)$$

so the semiamplitude of the pulsations is then

$$A=\frac{\epsilon}{2}\frac{R_{mag}}{R_{wd}}. \qquad (8)$$

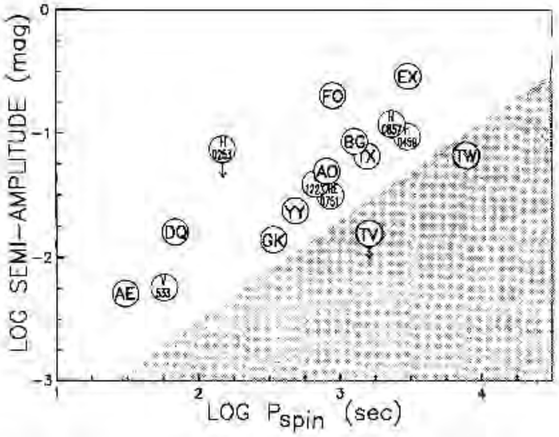

FIG. 12—Optical pulse amplitude vs. P_{spin}. The shaded region is normally inaccessible, where a good-quality 5-hr observation does not suffice to reveal the signal (amid the usual flickering noise of CV light curves). The stars roughly follow a $A \propto P^{0.65}$ relation.

Now it is natural to assume a magnetospheric radius equal to the corotation radius R_{cor} (where matter circulates in the disk with a period equal to the white dwarf spin period), because that is the place where gas can most easily slip onto field lines. For generality we assume $R_{mag}=kR_{cor}$, which implies

$$R_{mag}=k(GM_{wd}/4\pi^2)^{1/3}P^{2/3} \qquad (9)$$

and hence

$$A=\frac{\epsilon k}{2}(GM_{wd}/4\pi^2)^{1/3}P^{2/3}/R_{wd}=KP_{1000}^{2/3}, \qquad (10)$$

where K is a constant given by

$$K=12.5k\epsilon M_1^{1.0} \qquad (11)$$

(we use $R_{wd} \propto M_{wd}^{-0.7}$ as an approximate mass–radius relation).

This reproduces the *slope* of the empirical relation. For a typical white dwarf $M_1 \approx 0.7$, so the intercept is correct when $k\epsilon=0.007$. Now k cannot exceed 1 if accretion is to occur, and must exceed ~ 0.1 if the magnetosphere is not squashed all the way to the white dwarf surface. Thus the above explanation is viable if ϵ is in the range 0.007–0.07.

The direct contribution to ϵ from the shock-heated gas above the pole is negligible, so the more important contributor should be the reprocessing of X rays on the white dwarf. For a short accretion column (i.e., with a shock height $\ll R_{wd}$), nearly half of the X rays are intercepted and reprocessed to a very luminous component, with $T_e \sim 10^5$ K. This implies a bolometric correction 4–6 mag, which would yield $\epsilon \approx 0.003$–0.03. This suggests that the above derivation may well explain the period–amplitude relation.

Complications abound. For a fairly tall accretion column ($\gtrsim R_{wd}$), the white dwarf presents a smaller solid angle and hence is illuminated by fewer X rays, but reprocesses them at lower T_e. This is mitigated by the fact that much of the X-ray emission occurs at the base of the column (because $L_{brems} \propto N_e^2$). In Sec. 7.1 we will claim that ~80% of the expected X rays are not actually seen, which would lower the effective ϵ by a factor of 5 if they actually do not exist (i.e., do not contribute to the white dwarf heating). And if this accretion flow which does not produce hard X rays *does* exist, it must avoid the shock and deposit its energy over some unknown fraction of the white dwarf's surface. The effects of these complications on ϵ are, respectively, to lower it, raise it, probably raise it, lower it, and affect it in an unknown way. A realistic calculation of ϵ is a major research problem in itself!

Two additional simplifications are made in the above argument:

(1) Some inconsistency is incurred by comparing the theoretical amplitude of the spin pulse with the observed amplitude of the *dominant* pulse (which is sometimes a sideband). This is for the sake of having a uniform procedure, and to use data for stars where there is still some ambiguity about the exact value of the spin period.

(2) I cite this reprocessing model as only *one possible mechanism* for producing optical pulsations at the spin period. Reasonable arguments have also been made for the "accretion curtain" model, which situates the optical light at a greater distance from the white dwarf (Rosen et al. 1988; Hellier 1992). No preference is intended. Either model should tap gravitational energy with some characteristic efficiency, and hence produce some roughly constant value of ϵ.

In summary, the period–amplitude relation appears to be real, and I think the above derivation is probably correct in broad outline. It is likely that k and ϵ vary considerably from star to star, but not enough to cancel the huge effect of $P^{2/3}$ when P varies over a factor of 200.

6. INCIDENCE OF DQ HER STARS

6.1 Optical Selection

Our census contains selection effects. I think the most serious is basically the one encountered above in the period–amplitude relation, namely, that long-period signals are hard to detect in data streams of typical length, due partly to the small number of cycles encompassed, and partly to the presence of "red noise" which afflicts the light curves of all CVs. My rough estimate, based on perceptions of how frequently we find new members by increasing the diligence of our searches, is that we undercount the long-period systems by a factor in the range ~1.5–2.0. It is possible that the undercount is more serious, since the observed systems are close to the detection threshold in Fig. 12.

The short-period systems are a different story. Optical photometry can easily reach amplitude limits of ~0.001 mag for these stars, and it is easy to test for coherence since many hundreds of cycles elapse in one night. Since most of the bolometric luminosity must come from the inner disk, one generally expects the modulation to exceed 0.001 mag. And this is generally borne out by observation, since the three candidate stars show signals far above the detection threshold. On the other hand, both AE Aqr and V533 Her show much weaker oscillations when bright, for reasons not understood, and it may be that some stars hide their credentials (~permanently) because their accretion rates are too high. Here, also, an undercount by a factor of ~2 seems plausible.

Robinson and Nather (1977) present a list of null results in a search for rapid periodicities. Combining this with my own list of null results, I estimate that for periods below ~2 min, the observed incidence of DQ Her stars is ~4%.

6.2 X-Ray Selection

It has become a piece of parlor wisdom, sanctioned through repetition, that "most DQ Her stars are discovered from their X-ray emission." This is really not true. Inspection of Table 1 reveals that of the 18 certain and highly probable members, 9 were first discovered optically, and 13 had their pulsations first detected optically. But the evidence certainly supports a related proposition: *that the incidence of DQ Her stars among X-ray-selected* CVs (in practice, this means high F_x/F_V) *is much higher than in the general population of* CVs.[2]

We demonstrate this by considering all of the CVs detected by the scanning and nonfocusing X-ray telescopes of the 1970s; these consist of the 41 stars listed in the *HEAO-1* catalog (Silber 1992), plus GK Per and H 0253+193. This collection contains 14 DQ Her stars, and probably a few more since detailed X-ray and optical studies are still lacking for ~10 of these objects. Thus the DQ Her incidence seems to be ~40%, about ten times greater than among the optically selected CVs. A similar result applies to the AM Her stars, of which there are seven in the survey (and possibly some lurking among the unstudied objects). The incidence of AM Her stars seems to be ~20%, whereas polarimetry of CVs in general yields detections with an efficiency of only ~2% (Cropper 1986; Stockman et al. 1992).

Of course, it is easy to understand why systems with magnetically channeled accretion should be strong hard X-ray emitters. A larger fraction of their total accretion energy is budgeted for the final plunge to the white dwarf; and because the flow is collimated, it is less likely to yield energy while infalling, and more likely to form a strong shock during the supersonic encounter with the white dwarf surface.

It stands to reason that with the expected rapid growth in the ranks of X-ray-selected CVs, the lists of DQ Her stars should also swell greatly. So although the parlor wisdom of today is not true today, it could be true in a few years.

My estimate from all of this is that in a magnitude-limited sample (roughly the world of "known CVs"), about 3%–6% are short-period DQs, and about 5%–15% are long-period DQs. Their true frequencies are probably 2–3 times lower, since they are quite rare among the intrinsically faint stars which are the most common type of CVs.

7. X-RAY EMISSION

7.1 Theory Versus Observation

The simple theory of radially accreting white dwarfs, described in Sec. 2.1, predicts an X-ray luminosity

$$L_x \simeq GM\dot{M}/R \simeq 10^{34}\dot{M}_{17}\ \mathrm{erg\ s^{-1}}, \qquad (12)$$

where $\dot{M}_{17}$ is the accretion rate in units of 10^{17} g s^{-1}. To compare this with 2–10 keV observations, we assume a spectrum with $kT_{\mathrm{brems}} = 15$ keV, 50% of the original L_x radiated downward towards the white dwarf, and a white dwarf albedo of 0.3 for hard X rays. The line in Fig. 13 shows the resultant predicted dependence of 2–10 keV luminosity (which we will hereafter call the "hard X-ray" luminosity L_{hx}) on $\dot{M}$, and the circles show the data, taken from Table 1.

The main lesson from Fig. 13 is that as a class, the DQs are underluminous in hard X rays, by a factor averaging ~4 (excluding the three fastest rotators, which we will discuss later). Errors in distance really do not affect this conclusion, since they move the points along lines nearly parallel to the theoretical line. The underluminosity might depend on $\dot{M}$; at face value the data suggest $L_{\mathrm{hx}} \propto \dot{M}^{0.64 \pm 0.15}$. But this depends heavily on the stars of lowest and highest $\dot{M}$, and is not a secure conclusion.

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[2] And yet another related proposition: "most DQ Her stars are studied by people who are more interested in X-ray emission." This wavelength/aesthetic bias has been noticeable in discussions of these matters.

This is reminiscent of the famous "soft X-ray problem" in AM Herculis stars. To paraphrase King and Watson (1987) in their discussion of AM Hers, it should be called the *hard* X-ray problem, because the puzzle lies in why the observed hard X-ray fluxes are quite low compared to what is expected from radial accretion. The most likely solution is that most of the kinetic energy of accreting gas manages to avoid the shock and tunnel into the white dwarf, perhaps because it is highly clumped and takes the form of "bullets" (Kuijpers and Pringle 1982; Thompson et al. 1986; Frank et al. 1988).

Well, the DQs also show a hard X-ray problem, and since they too are powered by radial accretion, it is tempting to suppose that the same mechanism is at work. I think the AM Her analogy is a good one, and interpret the average underluminosity of DQs to mean that ~80% of the accretion energy avoids the shock and tunnels into the white dwarf, to reemerge (on some time scale) as EUV/UV light.

7.2 EUV: The Holy Grail of Energy Balance

I have studied this hypothesis to see if it is consistent with all other data on DQ Her. It requires a large EUV luminosity; is this compatible with the many nondetections from *EUVE* and the *ROSAT* wide-field Cameras? Yes, in my judgment it is. Most of the DQs are at distances >200 pc, which suggests that the interstellar opacity at EUV wavelengths may be too great. In addition, Table 1 shows that many have concocted by their own means (not well understood by us mortals) a huge column density of cool gas on the line of sight to the hard X-ray source, which would certainly destroy the visibility of an EUV source if it is also on *that* line of sight.

The most promising stars for study are: the nearest, those with no obvious signature of high N_H in the X-ray spectrum, those with high $\dot{M}$ (to maximize luminosity), and those that happen to be located in directions of low interstellar absorption. No one star is desirable from all of these viewpoints. The worst is certainly H 0253+193 (inside joke for *cognoscenti*, or for readers with a good memory!). AE Aqr, EX Hya, and YY Dra are nearby and only lightly absorbed, but their accretion rates are very low. V1223 Sgr and GK Per have high $\dot{M}$ but are horrendously absorbed (attested by a large 2200 Å depression). The most promising of all seems to be RE 0751+144, which has a fairly high $\dot{M}$, no large N_H in the hard X-ray spectrum, and is located in a direction where interstellar absorption is very light out to a distance of ~500 pc (Paresce 1984; Frisch and York 1985). Mason et al. (1992) found a strong soft X-ray/EUV component in this star, and it is a reasonable guess that this is the "missing 80%."

The searchlight luminosity can also be estimated by studying pulsations in emission lines, especially high-excitation lines which are almost certainly produced by photoionization. Patterson and Raymond (1985) point out that He II emission in nonmagnetic systems is too strong by ~5× to be ascribed to photoionization by hard X rays. I have repeated this calculation for the DQ Hers, and found a similar result: $L_{\rm hx}$ is ~10× stronger for the DQ Hers, and so is L(He II), therefore there is need for a luminous soft X ray ($E>54$ eV) component to power the line. This component should be part of the rotating searchlight, since all attempts to measure the pulses in high-excitation lines have revealed very large pulse fractions (Chanan et al. 1978; Penning 1985; Hellier and Mason 1990).

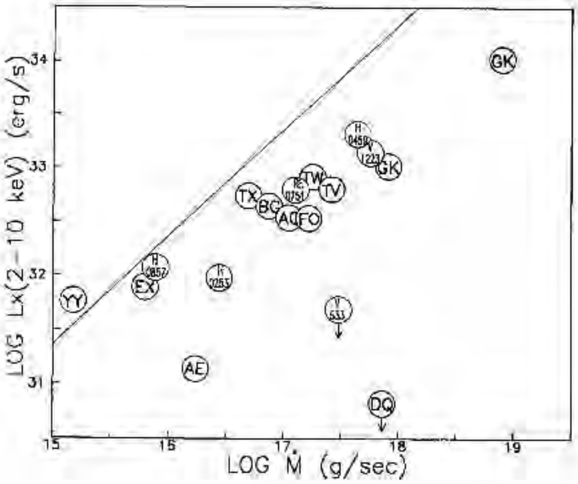

FIG. 13—$L_{\rm hx}[\equiv L_x(2\text{–}10\ {\rm keV})]$ vs. $\dot{M}$. The line represents the prediction from a simple model, Eq. (12).

7.3 Hard X-Ray Pulsations

While there are many hints that DQ Hers are spectacular EUV sources, if we could only see them, the hard X rays are highly penetrating and provide a firmer basis for our soaring flights of fancy. Many of the DQs show strong hard X-ray pulses as the white dwarf rotates, as expected. What exactly is the mechanism by which the pulse waveform is made?

King and Shaviv (1984) calculate the light curves expected from a tall, optically thin accretion column rotating in and out of view. The light curves are quasisinusoidal, with the detailed shape depending on binary inclination and magnetic obliquity. The geometry alone dictates the visibility of the emission region, so there is no energy dependence. Rosen et al. (1988) report a considerable energy dependence in the X-ray pulses of EX Hya, and develop an alternative "accretion curtain" model, in which absorption effects in the column produce the waveform.

Examination of many stars' pulse shapes at many energies (Norton and Watson 1989a) proves that photoelectric absorption is quite important, but so is geometry (since some stars show strong pulses even at very high energy). In general, the pulse wave forms need to be understood on a star-by-star basis; the reader should consult Norton and Watson's paper for an excellent study of these effects.

7.4 Orbital Modulations

A more puzzling feature is the orbital modulations seen in the X-ray light curves of DQs, discussed in detail by Hellier et al. (1993). The majority of X-ray emitting DQs show this effect, and since nearly all show a much harder X-ray spectrum during the minimum of the orbital light curve, it is probably due to photoelectric absorption in a structure which moves around the white dwarf with the binary period.

What structure is this? Most of the dips occur ~0.2 cycles before inferior conjunction of the secondary; this is when the bright spot at the edge of the disk should be nearest the line of sight to the white dwarf, so the bright spot is a prime suspect. However, to explain the obscuration in noneclipsing systems the gas must be at least 30° above the orbital plane, and that is somewhat surprising. It is also worrisome that the minima are fairly broad, some even quasisinusoidal; a structure at the outer edge of the disk would have to be very large and extended in azimuth to produce such eclipses.

Hameury et al. (1986) suggest that DQs may accrete directly from the secondary, without the mediation of a disk. This can ameliorate the above problems. Gas streaming from the secondary to the magnetosphere could easily be locked to the binary period, could rise well above the orbital plane (since it must do so eventually to accrete!), and could be quite extended in azimuth since it is likely to be sheared by the flailing magnetosphere. Since it involves gas streams, magnetic fields, and whirling dervishes, this scheme is not very well suited to produce *stable* X-ray dips—and indeed, the observations indicate that the dips tend to be quite unstable in depth and phase. I consider this explanation to be very promising, as did Norton et al. (1992b).

Does this mean that accretion probably *does not* proceed through a disk? Heavens, no! The evidence for accretion disks in DQ Her stars generally is quite vast: the V/R disturbance in the emission lines of DQ Her and EX Hya (Kraft and Greenstein 1959; Young and Schneider 1980; Gilliland 1982; Hellier et al. 1987), the relatively narrow and stationary emission lines suggestive of circular motions far from the white dwarf, the apparent grazing eclipses (Hellier 1991), the period–amplitude relation discussed above, and X-ray pulses at the spin period rather than at the orbital sideband (Table 1, see also Hellier 1991). It seems undeniable that in most stars, most of the accretion proceeds through a disk most of the time; but probably there is a "back-door" accretion flow which proceeds directly to the magnetosphere. Lubow (1989) describes how some of the flow can skim over the top of the disk. The amount of cool gas in that flow, required to obscure the white dwarf's X-rays at the orbital period, need not be large.

7.5 Size of the Emission Region

Observations of AM Her stars, notably the eclipsers, have demonstrated that both hard and soft X-rays emerge from a very small region, with a projected area on the white dwarf $\lessdot 1\%$ of the white dwarf's surface area. Do we have any such information for the DQ Hers?

Two indirect clues have been with us for a while. The X-ray and optical pulse shapes are approximately sinusoidal, which suggests a fairly large structure (King and Shaviv 1984). And the lack of any observable soft X-ray component, despite our physical argument that it must be there, could also signify a large accretion area (which would move the re-emergent radiation to the EUV, and hence make it more conveniently unobservable). The discovery of X-ray eclipses in H 0253+193 has provided a more direct clue: the measurement of ingress/egress times indicate a projected diameter of $\sim 1.5 \times 10^9$ cm (Kamata et al. 1991, see discussion in Sec. 2.4.11).

While direct, this last clue could be somewhat misleading. The estimate is valid if the secondary's edge is sharp, which Kamata et al. defend on the grounds that the X-ray spectrum does not change during ingress/egress. But this depends on a mere 5 min of exposure, and it does not seem wise to trust it completely without confirming evidence.

Some additional evidence already exists in the X-ray pulses. The binary inclination is very high, and it therefore seems very likely that the accreting pole is carried fully around the limb of the star. Yet the pulsed fraction is only about 30% (Koyama et al. 1991). This suggests an emitting region of a size comparable to the white dwarf.

8. HOW MANY KINDS OF DQ HER STARS?

Starting with the discovery of pulsations in AO Psc, several stars were rapidly found with rather high L_{hx}/L_v values (~1–5) and relatively long periods (12–21 min). This fostered speculation that these relatively slow rotators did not belong to the "DQ Her class" (which at that time included only DQ Her, V533 Her, AE Aqr, WZ Sge, and EX Hya) at all, but were an altogether new phenomenon. Stars in the new class were sometimes referred to as "intermediate polars," and the distinction was based primarily on period (since all intermediate polar fans agreed that EX Hya was "one of theirs").

But oddly enough, the accepted model for both classes of stars was, and is today, precisely the same! (Namely, Fig. 1). Is there any real distinction between these classes?

8.1 Dichotomy in Period?

The evidence for a bimodal distribution in period was always weak, but now seems to have evaporated completely. Figure 14 shows the spin period distribution, which is very broad and not suggestive of any dichotomy. This conclusion might change, of course, with a large increase in the number of available stars, or with a more carefully justified selection of which physical variable to use. But at present there is no evidence for a bimodal distribution in period.

8.2 Dichotomy in X-Ray Emission?

What about other grounds for distinguishing between these two proposed classes? From optical observations, there seems to be no distinction. The period–amplitude relation unites all the DQs, and the data on period changes are also at least approximately consistent with a simple spin-up theory (see below). But a glance at Table 1 shows one ground on which a distinction could be made. The three stars of shortest $P_{\rm spin}$ have hard X-ray luminosities and temperatures quite low compared to their confréres at longer $P_{\rm spin}$. This is shown in the upper frame of Fig. 15. Another sharp contrast exists in $F_{\rm hx}(2\text{–}10\ {\rm keV})/F_V$ (5000–6000 Å), a strictly observable ratio immune to uncertainties in distance and $\dot{M}$. This is shown in the lower frame of Fig. 15.

Is this sufficient reason to subdivide the class? I think not. It seems to me entirely reasonable that accreting magnetic white dwarfs could display very different properties of their X-ray emission, *depending solely on their rotation period*. In order for accretion to occur, we must have $R_{\rm mag} < R_{\rm cor}$, which means that in short-period systems the accretion disks approach quite close to the white dwarf. This can seriously deplete the energy available for the final plunge to the surface. A rough calculation yields the prediction that

$$\frac{F_{\rm hx}}{F_{\rm disk}} = 0.22(25kM_1^{1.0}P_{1000}^{2/3} - 1). \tag{13}$$

To convert this to $F_{\rm hx}/F_V$ we multiply by 13, the appropriate conversion between the bolometric and the 5000–6000 Å flux for the typical observed "disk" temperatures of ~12,000 K. Then we divide by 4, to account for the probable deficit of hard X rays discussed above. We also include reprocessing, by adding 5–10% of the full X-ray luminosity to the "disk" side of the ledger sheet. The predicted run of $F_{\rm hx}/F_V$ with $P_{\rm spin}$ is then given by the shaded curve in Fig. 15, bounded below by ($k=0.6$, $M_1=0.6$, 10% reprocessing) and above by ($k=0.9$, $M_1=0.9$, 5% reprocessing). By letting the disk temperature range from 8000 to 16,000 K, slightly broader limits are obtained, given by the dashed curves.

The data appear to be consistent with the general drift of the calculated curves, and even with the normalization, subject to the considerable caveat that the average underluminosity in $L_{\rm hx}$ is *assumed*, not truly understood.[3] I certainly see no support here for the idea that there are two classes of these stars.

There may be other factors (i.e., other than the shallower potential well) which tend to suppress hard X-ray emission in the fastest rotators. The accretion shock is likely to be only barely within the magnetosphere, so the infalling gas is less rigidly steered by the magnetic field lines, and hence the assumption of radial infall is likely to be less valid. Consequently the energy could be radiated in weak, oblique shocks, decreasing the pulsed fraction and robbing luminosity from the customary 2–10 keV bandpass.

The actual process by which the gas flow manages to move from Keplerian to radial is essentially unknown. It seems plausible that it might not matter much if the transition occurs far out in the disk, since not much energy is released there. But it presumably matters a great deal for the fast rotators. When the rotation rates differ by a factor of ~100, important details of the accretion flow may differ widely, without requiring any fundamental change in the physics.

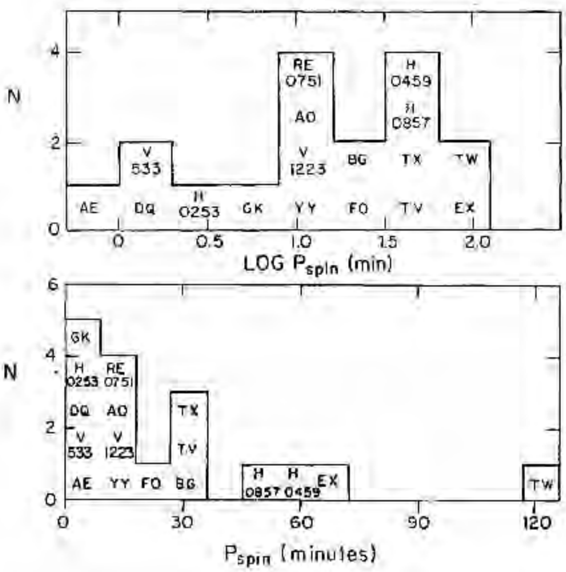

FIG. 14—Distribution of spin periods. No significant dichotomy in the distribution appears.

8.3 Nomenclature

For these reasons I think it unwise to seize upon the difference in X-ray properties as grounds for subdividing the class. And as for the proper name for these objects, the traditional variable-star nomenclature is warmly recommended, since it does not prejudice us to any particular model and will not need changing if interpretations change. Like the Holy Roman Empire, intermediate polars appear to be neither intermediate (there being only one class, in my judgment) nor, as a rule, polars (only 2 out of 18 show polarized light). It would be nice if the latter term would disappear.

9. RELATION TO AM HERCULIS STARS

The defining property of the DQ Hers is that they contain magnetic but asynchronously rotating white dwarfs. This is in contrast to their more famous cousins, the AM Her stars, which contain magnetic white dwarfs rotating in synchronism with the orbit. But the two classes are also commonly distinguished by an empirical rule of thumb: the AM Hers show strong circular polarization, and the DQ Hers do not. These criteria have now become slightly fuzzy, because polarization has been found in two obvious DQ Hers ($P_{\rm spin} \ll P_{\rm orb}$), and asynchronism has been found in two apparent AM Hers ($P_{\rm spin} \approx 0.98\ P_{\rm orb}$)!

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[3] Anyone violently opposed to this assumption is welcome to move the calculated curves upward by 0.6.

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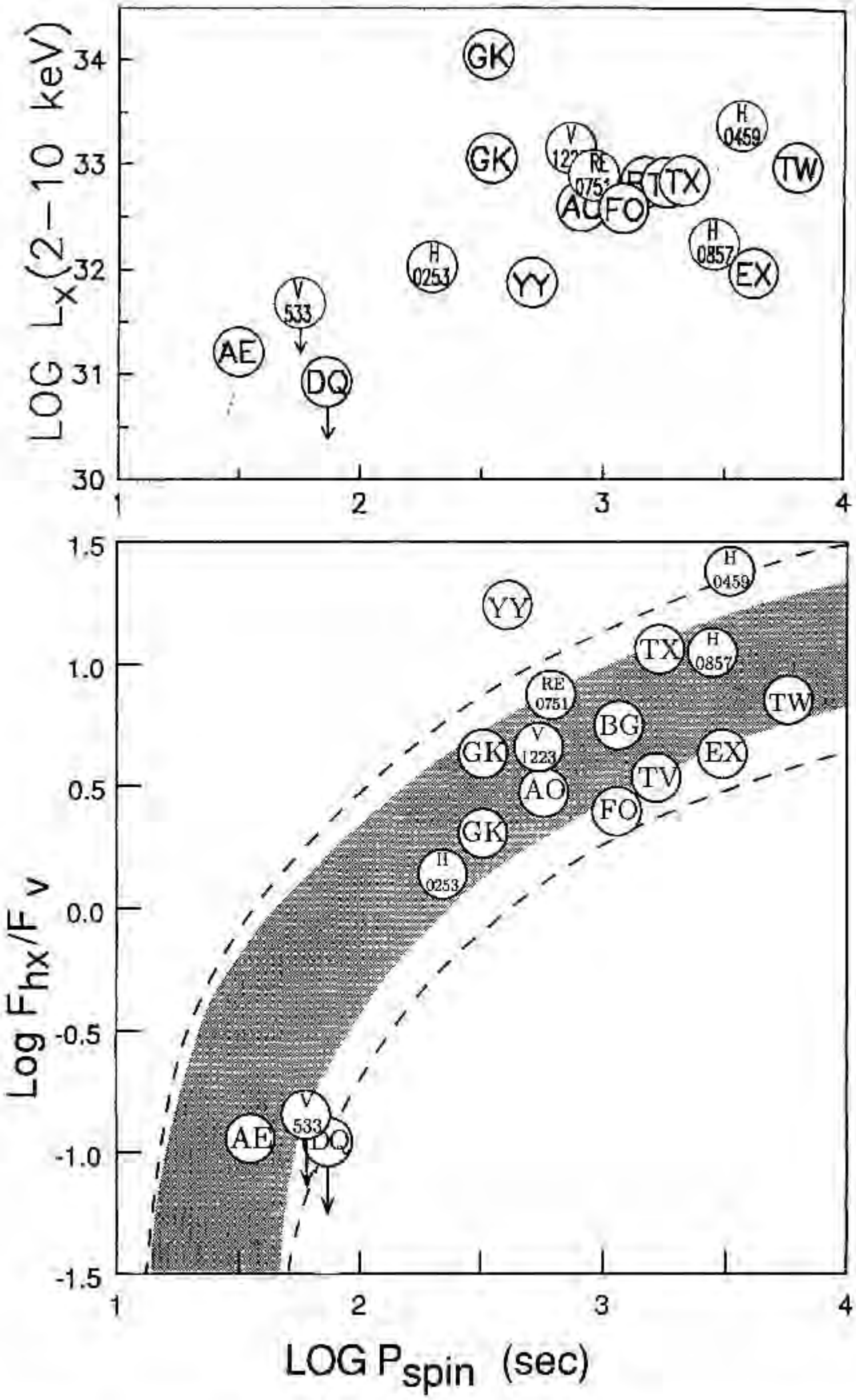

FIG. 15—*Upper frame:* L_{hx}(2–10 keV) vs. P_{spin}. *Lower frame:* F_{hx}/F_V (5000–6000 Å) vs. P_{spin}. The shaded region is the prediction from a model in which we assume the disk exists down to $R_{mag}=kR_{cor}$, the accretion flow becomes radial without further dissipation of energy, and 20% of that radial infall energy appears as a hard X-ray component with $kT=15$ keV. The upper boundary of the shaded region corresponds to ($k=0.9$, $M_1=0.9$), the lower boundary to ($k=0.5$, $M_1=0.5$). The dashed boundaries use the same limits, but relax some of the auxiliary assumptions (see text).

9.1 Condition for Polarization

It is difficult to imagine how to produce large circular polarization without the presence of magnetic fields. In particular, isolated magnetic white dwarfs show broad emission bumps at the fundamental cyclotron frequency

$$\nu=eB/2\pi mc=2.8\times10^{13}\ B_7\ \text{Hz}. \qquad (14)$$

The hot gas in an AM Her accretion column should be emitting at this frequency and its harmonics. But the gas is opaque to the fundamental and low harmonics, so energy is trapped and emerges as an unpolarized "blackbody" (because it is thermalized) component. At some fairly high harmonic the gas becomes optically thin, and polarized emission at this frequency results (Wickramasinghe 1988). The corresponding wavelength of the *n*th harmonic is

$$\lambda = \frac{10.7\ \mu\text{m}}{n} B_7^{-1} \tag{15}$$

suggesting that the polarization lies predominantly in the infrared for DQ Hers ($B_7 = 0.01 - 1$). This agrees with the experimental fact that circular polarization is not observed in most of the stars, and is seen to increase sharply into the infrared for the two stars with positive detections (BG CMi and RE 0751+144).

9.2 Condition for Synchronism

The fact that the X-ray and polarization features of AM Her stars recur on the orbital period proves that the white dwarfs rotate synchronously with the orbit. That synchronism must arise somehow from the stars' magnetism. We can get a rough estimate of the required μ by setting $R_{\text{mag}} = R_{\text{orb}}$ in Eq. (1) and applying Kepler's Third Law. Then the magnetic moment must satisfy

$$\mu_{32} = 110 M_1^{5/7} (1+q)^{7/12} \dot{M}_{17}^{1/2} P_2^{7/6}, \tag{16}$$

where $P_2 = P_{\text{orb}}/2$ hr. Typical values for AM Hers are $M_1 = 0.7$, $q = 0.25$, $\dot{M}_{17} = 0.1$, $P_2 = 1$, implying $\mu_{32} > 30$. It is much harder for long-period stars to synchronize: the required μ rises by a factor $P^{7/6}$, or even faster ($\propto P^{2.8}$) if the average $\dot{M} - P_{\text{orb}}$ relation is obeyed (Patterson 1984).

Two stars have been found with polarized emission recurring with a period slightly less than the orbital period (V1500 Cyg: Schmidt et al. 1988; BY Cam.: Silber et al. 1992). While this technically puts these stars in the DQ Her class, they resemble AM Her stars so closely that they are usually regarded as AM Hers that have "gone astray" (possibly because of the loss of phase lock in a classical nova eruption), rather than as yet another uninvited and dreaded partition of the DQ Her class.

A high *B*-field favors synchronism, and favors the detection of circular polarization since it moves the polarized flux towards visible wavelengths. But the two conditions are not exactly equivalent, nor does the empirical data support an exact DQ/AM dichotomy. The mild asynchronism in BY Cam and V1500 Cyg suggests that AM Her status can be marginal, especially in long-period stars where a rise in $\dot{M}$ is more likely to break the lock.

We can simplify (16) by assuming the average $\dot{M} - P_{\text{orb}}$ relation, adopting a white dwarf mass–radius relation, and absorbing the weak $(1+q)$ dependence into the P_{orb} factor. The result is that magnetic white dwarfs synchronize when

$$B_7 \lesssim 1.5 M_1^{3.1} P_2^{2.8}. \tag{17}$$

The essential reason for these sharp dependences is the rapid R^{-3} falloff of the magnetic dipole.

10. OUTBURSTS, LOW STATES, ETC.

Like all CVs, the DQ Hers generally have "high" and "low" states, plausibly associated with changes in accretion rate. The etiology of these excursions in brightness is quite poorly known, because most of the variability is mild and/or infrequent. There is not much resemblance to dwarf nova eruptions, although some have argued that disk instabilities can mimick the observed light curves if a magnetic cavity at the disk center is present (Cannizzo and Kenyon 1986; Angelini and Verbunt 1989; Kim et al. 1992). Some of the rather sparse data is discussed by Hellier (1993c) and Garnavich and Szkody (1988).

11. PULSE PERIOD CHANGES AND ACCRETION TORQUES

The white dwarfs' moments of inertia are sufficiently small that torques from the disk should cause measurable period changes. And they are sufficiently large that cycle count is easy to maintain and measurement accuracy easy to improve over long base lines. Both statements are true, and sensitive $\dot{P}$ measurements are available for nine of the DQ Hers, yet the interpretation of $\dot{P}$ is still quite uncertain, for reasons we will now explore.

11.1 Theory

At first thought, one would expect all the DQ Hers to spin up rapidly due to the accretion of angular momentum from the disk. But this cannot be a good description of reality, since one is spinning down, and since most are rotating too slowly to have undergone rapid spin-up over long periods of time. Ghosh and Lamb (1978a,b) explained why magnetic compact stars accreting in a disk should experience a torque more complex than the simple and easily calculated "matter torque." They characterized the star as rotating with a "fastness parameter" $\omega_s = \Omega_{\text{star}} / \Omega(R_{\text{mag}})$, where $\Omega(R_{\text{mag}})$ is the angular velocity at the magnetospheric radius. When $\omega_s \approx 0$ the star is a "slow rotator" and the matter torque dominates. When the white dwarf rotates faster, some of its field lines drag in the more slowly rotating disk (outside of R_{mag}), and a spin-down torque is exerted which counters the matter torque. For some critical value of $\omega_s (\equiv \omega_{\text{crit}} = 0.35\text{–}0.85$, Lamb 1988), the spin-down torque cancels the matter torque and the star is in *spin equilibrium*. For $\omega_s > \omega_{\text{crit}}$, the star should spin down, and accretion is stopped or highly inhibited.

The resultant period change is given by

$$\dot{P} = -1.7 \times 10^{-11} \mu_{32}^{4/7} M_1^{1.0} P_{1000}^2 \dot{M}_{17}^{6/7} n(\omega_s), \tag{18}$$

where

$$n(\omega_s) \approx 1.4 \frac{[1 - (\omega_s / \omega_{\text{crit}})]}{1 - \omega_s} \tag{19}$$

is the dimensionless torque function given by models of the Ghosh and Lamb type.

A reasonable approximation to this theory, *mutatis mutandis*, is shown in Fig. 16. The little girl attempts to accrete onto a fast rotator, but is expelled by the centrifugal barrier. Noting her lack of world-class speed, the kindly operator slows the carousel down to where she can

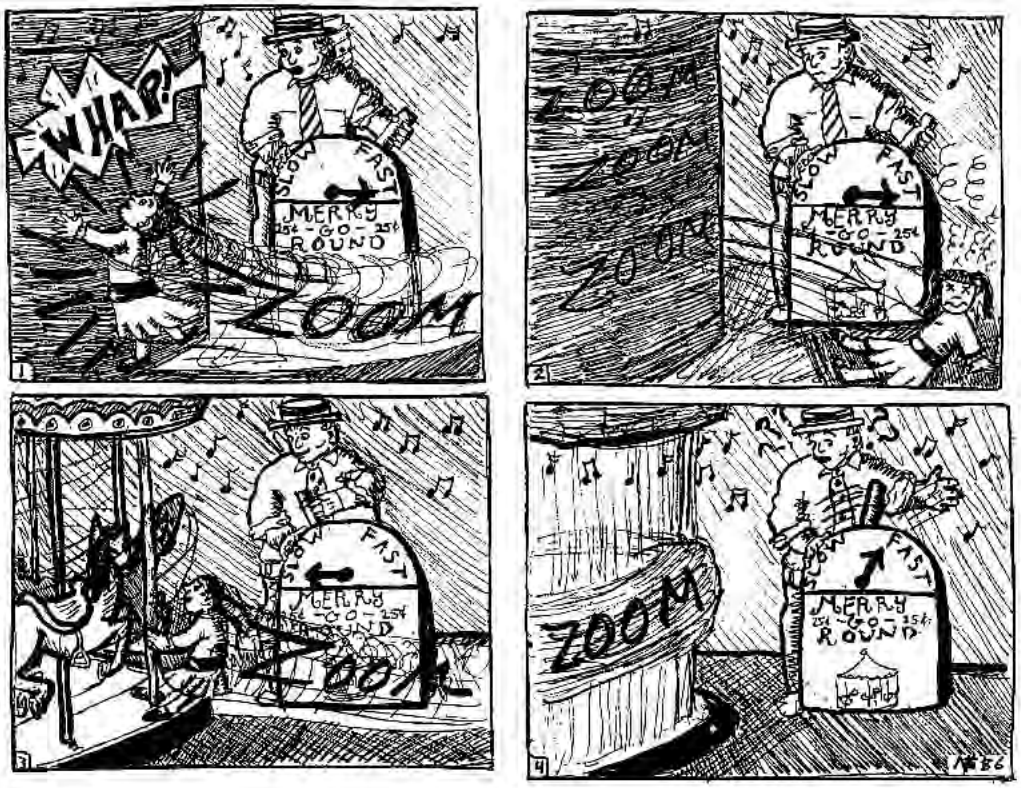

FIG. 16—Accretion does not always work; angular momentum is an important barrier. The little girl cannot quite get onto the "field lines" of the rapidly spinning carousel, so the friendly operator slows it down to where it corotates with her approach speed. However, as shown in the last frame, the operator does not necessarily understand the theory of the angular momentum exchange any more than we do.

approach with corotation speed or faster ($k \lesssim 1$), allowing her to accrete onto and spin up the carousel.

11.2 Comparison with Observation

There are two ways to learn the magnetic moments. In the first approach, favored by evolution-minded theorists, one assumes that the stars are near spin equilibrium, implying $\omega_s = \omega_{\rm crit}$ and making Eq. (18) useless. However, the fastness parameter can be written as

$$\omega_s = 0.041 P_{1000}^{-1} \dot{M}_{17}^{-3/7} M_1^{-5/7} \mu_{32}^{6/7} \qquad (20)$$

and this equation can be solved (with $\omega_{\rm crit} = 0.6$, say) to yield μ_{32}. This is also called the "fast rotator" assumption. In the second case, favored by diligent observers who desperately want to believe that their Herculean labors to discover $\dot{P}$ actually mean something, one solves Eqs. (18) and (19) with some prescription for ω_s. The simplest prescription is the "slow rotator" assumption, with $\omega_s \approx 0$.

Which approach is better? East of the mid-Atlantic ridge, spin equilibrium is a popular choice. Norton and Watson (1989b) gave a thorough discussion of these issues, assumed spin equilibrium,[4] and concluded that for disk accretion the data favors $\mu_{32} \approx 10$. King et al. (1985) and Hameury et al. (1986) also argued for typical values $\mu_{32} \approx 10$–100.

In Table 2 I present the deduced values of μ_{32} based on these alternate assumptions and the estimates in Table 1. Assuming spin equilibrium, the median value of μ_{32} among all 17 stars is 20. Norton and Watson deduced values slightly lower, by adopting a smaller ω_s (0.35) and different values for $\dot{M}$. The results are fully consistent, except for the stars of shortest $P_{\rm spin}$ (for which I warmly recommend my numbers; Norton and Watson deduced $\dot{M}$ from $L_{\rm hx}$, which cannot possibly be right for these stars).

Still assuming spin equilibrium, Fig. 17 shows the run of μ with $P_{\rm spin}$, indicating a correlation roughly given by

$$\log \mu = 30.09 + 1.06 \log P_{\rm spin} . \qquad (21)$$

In deriving this, I have excluded the points for YY Dra and AE Aqr, because those stars have mean accretion rates which are extremely low for their orbital periods, suggesting that they may be very far from equilibrium.

This is a sensible relation, and might even be true. The causal relation implied here is that *the magnetic moment controls the spin rate* (after a minor consultation with $\dot{M}$): stars of low μ have disks with small central cavities and are wantonly spun up, while stars of high μ live in disks with large cavities and must rotate slowly to accrete from slow-moving gas far out in the disk.

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[4] They are both hard-working observers, but do not work explicitly on $\dot{P}$ measurements, so this probably does not contradict the proposed sociological distinction.

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TABLE 2
Estimated Magnetic Moments of White Dwarfs
(10^{32} G cm^3)

Star	Assumed Rotation "Fast"	"Slow"
AE Aqr	0.01 – 0.04	< 0.03
V533 Her	1 – 3	< 3
DQ Her	1 – 3	1 – 3
H0253+193	0.8 – 4	
GK Per	10 – 30	1.5 – 4
YY Dra	1 – 3	
V1223 Sgr	20 – 50	
AO Psc	8 – 30	10 – 30
RE 0751+144	10 – 30	
BG CMi	15 – 50	1.5 – 5
FO Aqr	15 – 40	0.2 – 1
TV Col	30 – 90	
TX Col	20 – 50	
VZ Pyx	20 – 70	
V1062 Tau	100 – 400	
EX Hya	20 – 50	0.4 – 2
TW Pic	100 – 400	

Table 2 shows that smaller values, averaging $\mu_{32} \approx 1$–4, come from assuming *slow* rotation. But two of the stars, V1223 Sgr and FO Aqr, are observed to have episodes of spin-down, which rules out slow rotation. Can we certify the five stars spinning up as slow rotators? No, because their spin-up might just reflect a short-lived episode of high accretion, which would hardly be unusual for CVs.

On balance, I am inclined to believe the spin-equilibrium argument for most of the DQs, mainly because it solves the problem of why the observed spin-up/spin-down time scales are so short (by denying them evolutionary significance). We should know the answer soon; spin equilibrium predicts that $\dot{P}$ will not be steady, but will wander on time scales of years to decades.

Most of the estimated magnetic moments are in the range $\mu_{32} = 10$–100, slightly below the AM Her stars which have $\mu_{32} = 70$–200. But there is no support here for the view that DQs comprise a truly separate population (Wickramasinghe et al. 1991, hereafter WWF; King and Lasota 1991). The distribution in Fig. 17 includes some possible overlaps with AMs, and also extends at least as low as $\mu_{32} = 1$.

12. QUASIPERIODIC OSCILLATIONS

Two stars show dramatically different periodic behavior when they brighten: AE Aqr (Patterson 1979a) and GK Per (Mazeh et al. 1985; Patterson 1991). In both systems the accretion light brightens by several magnitudes, and the stable optical periodicity is replaced by a QPO at slightly lower frequency. The QPOs are erratic, and not much is known about how the periods develop in outburst. Patterson (1991) remarked that in two observations of GK Per, the period was longer when the star was brighter, consistent with the idea that the QPOs originate from the illumination of blobs orbiting at the magnetospheric radius. But this certainly requires a more extensive study.

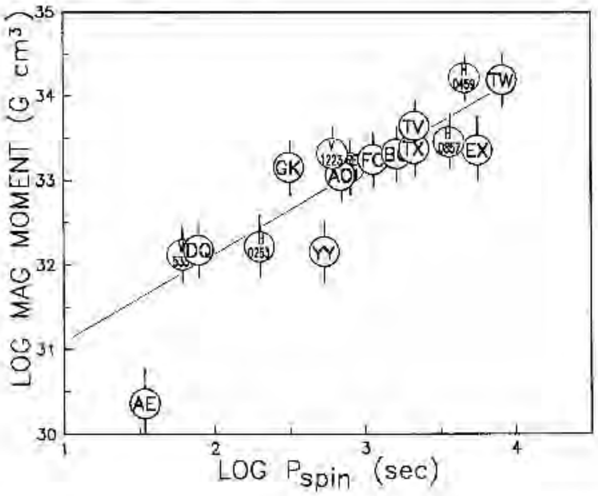

FIG. 17—Estimates of the white dwarf's magnetic moment, assuming that all are in spin equilibrium. The straight line is Eq. (21). Error bars show the effect of random errors in $\dot{M}$ and M_1. A systematic error from $\omega_{\rm crit}$ is possible, since $\mu \propto \omega_{\rm crit}^{7/6}$ ($\omega_{\rm crit} = 0.6$ is assumed).

Most of the DQ Hers with $P_{\rm spin} < 6$ min show these effects, but none of the longer-period stars. This could be a selection effect, either because of inadequate frequency resolution (during a typical 4-hr observation, insufficient cycles may elapse to cleanly separate the periodic signal from a QPO), or because of low amplitude (detection of weak signals is easy when the period is short, hard when it is long).

13. HIGH-SPEED SPECTROSCOPY

Some DQ Hers display emission-line profile variations at the spin period (Penning 1985; Hellier et al. 1987, 1990a, 1991; Buckley and Tuohy 1989, 1990). This is potentially a very rewarding observation if the phase of the continuum pulse is simultaneously known; the emission line carries velocity information, so it can be used to specify the location of the spinning searchlight as a function of time. Hellier and Mason (1990) reviewed the literature and concluded that in most cases the line represented "accretion-column" emission, with X-ray and optical maxima occurring at maximum blueshift. However, the result on DQ Her (CNM) suggested that the emission lines indicate motion in the disk rather than the column. These studies should be carried out for each of the DQs, and promise to deliver great diagnostic information on accretion flows in the binary.

14. NONTHERMAL EMISSION: RADIO AND GAMMA RAYS

Expanding nova shells are famous for their large radio luminosity, arising from free–free emission in the wind, but nearly all other CVs are feeble radio emitters (for reviews, see Chanmugam 1987; Cordova et al. 1983). The exceptions are, however, quite noteworthy! The only detected radio sources among quiescent CVs are AM Her (Dulk et al. 1983), AE Aqr (Bookbinder and Lamb 1987; Bastian et al. 1988), V834 Cen (Wright et al. 1988), and V471 Tauri (Patterson et al. 1993)—all systems with magnetic white dwarfs. Thus we have a solid empirical clue: *white dwarf magnetism is needed to power the radio source.*

Nevertheless, it is unlikely that the white dwarf alone powers the radio source, because isolated magnetic white dwarfs are not strong radio sources. In the case of V471 Tau the radio emission appears to show broad minima near the phase of white dwarf eclipse, which suggests that the emission comes from a fairly large cloud between the stars. A plausible mechanism for such "interstellar" radio emission is the acceleration of charged particles along the lines where the magnetic fields of the white dwarf and the secondary collide and reconnect. This is a process known to accelerate charged particles near sunspots, the Earth's magnetosheath, and laboratory plasmas. It seems especially plausible for the rapid rotators, which continuously feed the interaction region with fresh magnetic field lines.

Pulsed optical emission from AE Aqr was reported recently by a group studying Cerenkov radiation from the upper atmosphere (Meintjes et al. 1992). The optical photons signify the arrival of TeV gamma rays, which must be emitted in enormous quantities ($L_\gamma \sim 10^{32}$ erg s^{-1}). Along with the radio emission, this suggests that nonthermal processes play an important role in the binary. Mechanisms for accelerating protons to very high energies at the disk–magnetosphere boundary have been discussed by Cheng and Ruderman (1991) and Haswell et al. (1992).

15. ORIGIN AND EVOLUTION

Not much is known about the origin of the magnetic white dwarfs in CVs. About 2% of isolated white dwarfs are magnetic (Schmidt and Liebert 1987), and these are plausibly attributed to the population of A stars that are observed to be magnetic on the main sequence (also ∼2%, Landstreet 1992). I have estimated above that ∼10% of CVs are magnetic. These numbers are somewhat discrepant, and some appeal to magnetism in *producing* the CVs may be needed. "Cooperative magnetic braking" is a possible way to enhance production somewhat (Liebert and Stockman 1985).

Their subsequent evolution is another matter. The orbital period distribution contains a very striking clue: nearly all DQ Her stars are above the period gap, and nearly all AM Hers are below the period gap. Recognition of this led to the quite reasonable hypothesis that the DQs are basically the ancestors of the AMs (Chanmugam and Ray 1984; King et al. 1985). This depends on the assumption that the magnetic field strengths are basically similar, and to believe that you have to explain why the DQs are largely unpolarized. Chanmugam and Ray (1984) suggested that dilution by an unpolarized component (presumably the disk) could do it, but WWF found that it is quite difficult to hide the polarized light in this way. Thus the recent movement of theorists (WWF, Lamb and Melia 1988; King and Lasota 1991) has been towards the view that the field strengths in DQs are much lower. As we have seen above, this conflicts somewhat with the idea of spin equilibrium, as well as the 8–18 MG measurement in RE 0751+44 (Piirola et al. 1993).

Insisting on strictly lower field strengths in the DQs has other unpleasant consequences. It means the AMs cannot come from DQs, and it leaves the DQs without any reasonably abundant population of objects to evolve into. The theorists solve the first problem by postulating the existence of yet another class of magnetic CVs (groan!): nonsynchronous high-B systems at long $P_{\rm orb}$, probably without disks. Various excuses are given as to why we do not yet observe, or properly recognize, these stars.

My own opinion is that with just a little allowance for uncertainties in theory and observation, the first problem would be greatly eased. RE 0751+144 is an absolutely excellent ancestor for an AM Her star, and it is quite possible that a few other known DQs have the high fields required to be plausible ancestors. (Stars near the top of Fig. 17 are obvious candidates). A few DQs may be sufficient to produce all the presently known AMs, because the DQ lifetimes are probably ∼10× shorter. For this reason I see no need to postulate the existence of a new class of "hard-to-find" DQ Hers. The existing ones are hard enough to find!

The second problem is harder: where are the low-field short-$P_{\rm orb}$ stars which *most* DQs should evolve into? I have no persuasive answer to this, but I note that they would be intrinsically faint stars (because the short $P_{\rm orb}$ implies a low $\dot{M}$) and might lack the dwarf nova outbursts (because they do not have normal disks) which usually call attention to such objects.

Like nearly everything in the evolution of close binary stars, these issues are quite fascinating, important, and unresolved!

16. SUMMARY AND THE VIEW AHEAD

(1) Basic data are presented for 18 confirmed and very likely DQ Her stars. These are "white dwarf pulsars," the degenerate-dwarf analog of the accretion-powered high-luminosity pulsating X-ray sources. We briefly discuss the credentials of four other good candidates, and several other stars previously suggested as members.

(2) In general, these stars agree pretty well with the predictions made by the theory papers of the 1970s. Most are very hard X-ray sources, and can only be powered by accretion of radially infalling gas. Many show orbital sidebands, as also predicted (Katz 1975). Two show circular polarization, validating the hypothesis that a strong magnetic field is present. The magnetic moments probably average $\sim 10^{33}$ G cm^3. I believe the evidence greatly favors the existence of toroidal disks like that of Fig. 1, although some accretion probably occurs without the mediation of a disk.

(3) Observations have also revealed many features not predicted by any theory, and these are mighty interesting. Orbital modulations, caused by photoelectric absorption, are frequently observed in X rays, even when the binary inclination is low. This indicates that some portion of the

mass-transfer stream flows over the disk and strikes the magnetosphere directly, with memory of orbital phase intact.

(4) Empirical evidence firmly establishes that much of the radiant energy we receive is the result of "reprocessing" of other photons, and perhaps also of kinetic energy directly (in the form of "bullets" which the white dwarf in Fig. 1 is feebly trying to guard against). The clearest proof is *the existence of orbital sidebands of the spin frequency,* which attest to the power in the spinning searchlight. White and Marshall (1981) pointed out that in AO Psc the observed amplitude of the $\omega - \Omega$ optical signal is much too high to be powered by the known X-ray luminosity in the searchlight. This is actually true for all the DQs in which the orbital sideband is strong. The observed phase shifts and oscillation colors establish that it must also be true for DQ Her itself. *The searchlight must be powerful at energies we do not detect,* probably EUV.

(5) The $L_{\rm hx}(\dot{M})$ relation reinforces this conclusion: the luminosity in hard X-rays appears to be too low by a factor averaging ~ 4. The easiest way to account for this is to suppose that $\sim 80\%$ of the accretion energy manages to bypass the shock and burrow directly into the white dwarf. This should produce a strong EUV component which will be hard to see directly, but could be constrained by the study of the high-excitation emission lines.

(6) During episodes of high accretion, the optical periodicity in some stars tends to disappear, for reasons which no one understands. Sometimes in its place there are QPOs, usually at slightly lower frequency. No one understands those either. Because these exist in well-certified DQ Hers, it is possible that stars showing *only* a persistent QPO are closet DQ Hers, with the stable signal hidden in the flapping robes of the QPO. TT Ari, V795 Her, and H 0551 − 819 are good candidates.

(7) Long-term changes in the pulse period have been faithfully tracked by observers, but their interpretation is still murky. An improved theory of angular momentum exchange at the disk-magnetosphere boundary would be very helpful.

(8) Calculations of the expected energy release from accretion models depend crucially on the height and width of the accretion column (partly through reprocessing on the white dwarf surface), and observers should do a better job of learning this. Progress may come now through the study of the eclipse profile of H 0253 + 193 (Kamata et al. 1991), and the X-ray or ultraviolet pulse profiles of DQs (Norton and Watson 1989a; Norton 1993; Eracleous et al. 1994).

(9) Equally annoying is the ignorance of k $(= R_{\rm mag}/R_{\rm cor})$. I can't figure out how to learn this; but if someone else can, the treasure trove of the world's $\dot{P}$ data, accumulated over decades and still really awaiting a proper interpretation, is theirs for the taking.

(10) In order to produce observable periodicities, DQ Her stars must be *oblique* rotators, yet previous theories are limited to the *aligned* rotator case. This is probably a crucial difference, since the magnetic pressure at a given place on the magnetospheric boundary should vary by a factor of ~ 2 as the white dwarf rotates. I promise to read carefully any theoretical paper, no matter how formidable, which purports to remove this restriction!

(11) To my eye there appears to be just *one* DQ Her phenomenon, not two or more. The range of $P_{\rm spin}$, $L_{\rm hx}$, and $F_{\rm hx}/F_V$, as well as the period–amplitude relation, can be reproduced in a simple model with the magnetic moments continuously distributed in the range 10^{32}–10^{34} G cm^3. In fact, the high-field DQs appear to merge with the AMs, suggesting that the DQ/AM dichotomy is itself merely an accident of zoology. Channeled accretion onto a magnetic white dwarf is probably a single phenomenon, with synchronism broken whenever $B_7 \lesssim 1.5 M_1^{3.1} P_2^{2.8}$.

(12) The *evolution* of DQ Hers is a problem. If their field strengths were $\sim$10–40 MG they would be plausible ancestors of AM Her stars, which are clustered at short $P_{\rm orb}$ as a simple theory would predict. But the estimated field strengths appear to be lower. Although we could possibly produce all the AMs from a few DQs (because the DQ lifetimes are expected to be short), that would leave no other abundant class of object for *most* DQs to evolve into. Such problems are likely to keep us busy for a while.

(13) Despite their rarity, DQ Her stars appear to be the brightest radio emitters among CVs. One of them, AE Aqr, may be a spectacular source of pulsed TeV gamma rays. This suggests that these binaries have efficient means for producing relativistic electrons and protons, an aspect that deserves much more study by both theorists and observers.

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