CATACLYSMIC VARIABLES, HUBBLE-SANDAGE VARIABLES AND η CARINAE

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The Hubble-Sandage variables are the most luminous stars in external galaxies. They were first investigated by Hubble and Sandage (1953) for use as distance indicators. Their main characteristics are high luminosity, blue colour indices, and irregular variability. Spectroscopically they show hydrogen and helium in emission with occasionally weaker FeII and [FeII], and no Balmer jump (Humphreys 1975, 1978). In this respect they closely resemble cataclysmic variables, particularly dwarf novae. In the quiescent state dwarf novae show broad H and HeI, together with a strong UV continuum. Weak FeII in emission has been observed in U Gem and SS Aur (Warner 1976). The Balmer jump is either not present, or weakly in emission. The principal spectroscopic difference is the increased breadth of the occasionally doubled emission lines.

In contrast to the spectroscopic similarities, the luminosities could hardly differ more. Rather than being the brightest stars known, quiescent dwarf novae are as faint or fainter than the sun.

I suggest that the close correspondence between the spectral appearance of the two classes combined with the difference in luminosity is well accounted for by a model of Hubble-Sandage variables in which the same physical processes are occurring, but on a larger scale. The spectral characteristics of cataclysmic variables are generated by infall of gas through an accretion disk onto a white dwarf (Bath et al. 1974). The outer disk radii are $\sim 5 \times 10^{10}$ cm. The Hubble-Sandage variables would result from similar physical conditions (temperature, density etc.) being produced in an accretion disk which was geometrically larger, and therefore radiating a larger total flux. The occurrence of occasional nova-like behaviour in Hubble-Sandage variables is some support for this identification (see below).

I assume the Hubble-Sandage variables contain a main sequence star in a mass transferring binary with a separation $> 10^{12}$ cm. This separation allows an accretion disk to be formed around the main sequence star, and allows a more massive, evolving primary to be accommodated

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within the companion's Roche lobe. The major differences affecting accretion result from the much-reduced gravitational potential at the stellar surface, and the possibility of central masses greater than $\sim 2M_\odot$.

At the accretion rate $\dot{m}$ gs^{-1}, the luminosity due to accretion is $L = GM\,\dot{m}/R$ and the characteristic source temperature, $T = (L/4\pi\sigma\, R^2)^{1/4}$. To have the same spectral appearance as that produced by an accretion disk around a white dwarf, the accretion rate must be increased by a factor $\dot{m}_{MS}/\dot{m}_{WD} = (R_{MS}/R_{WD})^3\ (M_{WD}/M_{MS}) \sim 10^5$ to 10^7 (for masses $1 < M_{MS}/M_\odot < 100$). The ratio of luminosities is then $L_{MS}/L_{WD} = ([\dot{m}_{MS}\ R_{WD}\ M_{MS}]/[\dot{m}_{WD}\ R_{MS}\ M_{WD}]) = (R_{MS}/R_{WD})^2 \sim 10^4$ to 10^6. The obvious conclusion is demonstrated that the accretion luminosity of a main sequence star with a disk structure similar to that of a quiescent dwarf nova is very much brighter. It will have a luminosity $\sim 10^{36}$ to 10^{39} erg s^{-1}.

This model may be examined in greater detail using steady disk models (Shakura and Sunyaev 1973). The consequences of time-dependence in the disk may be shown to be unimportant. Assuming the disk is optically thick, which is valid so long as $T > 10^4$, then the temperature distribution as a function of radius and accretion rate is given by:

$$T(R) = (3GM\dot{m}/8\pi\sigma\ R_{MS}^3)^{1/4}\ (R/R_{MS})^{-3/4}\ (1 - [R/R_{MS}]^{-1/2})^{1/4} \qquad (1)$$

The temperature has a maximum at a radius $\sim 1.4\ R_{MS}$, and then decreases outward. The maximum disk temperature is given by:

$$T_{MAX} = 0.488\ (3GM\dot{m}/8\pi\sigma\ R_{MS}^3)^{1/4} = 8.3 \times 10^3\ \dot{m}_{20}^{1/4}\ (M/M_\odot)^{1/4}\ (R/R_\odot)^{-3/4} \qquad (2)$$

where $\dot{m}_{20} = \dot{m}/(10^{20}\ gs^{-1})$.

In Figure 1a the variation of T_{MAX} with $\dot{m}$ is shown for main sequence stars in the range 0.5 to 121 $M_\odot$. Radii are from Schwarzschild and Härm (1958), Iben (1965), and Stothers (1963). The associated luminosity changes are shown in Figure 1b. The variation of T_{MAX} and L is also shown for white dwarfs (cataclysmic variables) and a 1 $M_\odot$ neutron star (binary X-ray sources) for comparison.

Cut-offs exist at both high and low temperatures. Disk temperatures fall below 10^4 K with low accretion rates and the rapid fall in opacity leads to the disk becoming optically thin. In these conditions present models are not applicable. Radiation will be emitted in the lines with no strong continuum. Stars in this condition are likely to be found amongst the Stephenson-Sanduleak emission line objects, and symbiotic stars. For massive main sequence accretors a second cut-off exists, at low temperatures. For $M > 9\ M_\odot$ the nuclear luminosity is greater than the accretion luminosity at low accretion rates. This region is shown by heavy shading.

At high temperatures disk solutions break down when the luminosity becomes supercritical and radiation pressure disrupts the disk (Shakura and Sunyaev 1974). This bounday occurs at $L = L_{ed} = 4\pi\ GMc/\kappa$ and is shown in Figure 1 for a scattering opacity with $X = 0.7$. The behaviour of sources in the supercritical regime is discussed below.

It is evident from Figure 1 that accreting main sequence stars give a satisfactory model of Hubble-Sandage variables, simply through scaling accretion disk structure from the white dwarf to the main sequence case. With accretion rates 10^{20} to 10^{24} gs^{-1}, maximum disk temperatures are the same (10^4 to 4×10^4 K) as quiescent dwarf novae with accretion rates 10^{14} to 10^{17} gs^{-1}. The disk structure will be similar (Equation 1), simply scaled to larger radii. This larger disk has a luminosity ~ 10^{38} erg s^{-1}. To generate the highest luminosities (~ 10^{39} erg s^{-1}) massive main sequence stars (> 9 $M_\odot$) are required, with accretion rates ~ 10^{23} g s^{-1}. Accretion disks around massive main sequence stars will form the brightest Hubble-Sandage variables.

It is easy to show (Bath, in press) that the other physical properties apart from the temperature will be similar in the two cases at these rates. The disk optical thickness is $\tau_{MS} \sim 10^3$ and $\tau_{WD} \sim 10^2$. Both are well into the optically thick regime. The surface density differs somewhat, with $\Sigma_{MS} \sim 10^{3-4}$ g cm^2 and $\Sigma_{WD} \sim 10^2$ g cm^2. Density differences may affect the spectrum and could be responsible for the strong FeII lines observed in some Hubble-Sandage variables.

The differences in line broadening are easily accounted for. The broad, doubled lines in cataclysmic variables are caused by emission from material in the disk moving with Keplerian velocities. The maximum disk velocity is $V = (GM/R)^{1/2}$, with an orbital period $P = 2\pi\ (R^3/GM)^{1/2}$. In the mass range $0.5 < M/M_\odot < 121$ the periods range from $1 < P < 14$ hours and velocities $400 < V < 1200$ km s^{-1}. In the white dwarf case $10 < P < 60$ sec and $2{,}000 < V < 5{,}000$ km s^{-1}. Thus, the line broadening in main sequence accretion disks will be 2 to 10 times less than that observed in cataclysmic variables, in agreement with that observed in Hubble Sandage variables.

Both classes lie in roughly the same region in the two-colour diagram, U-B ~ -1.0 and B-V ~ 0.0. The absence of the Balmer jump in both cases is due to the spectrum being composed of contributions to the integrated light from radii at a range of temperatures and luminosities in the disk.

The required mass transfer rates are possible in principle, particularly if the companions are giants. Observed variability (Rosino and Bianchini 1973) is due to fluctuations in the mass transfer rate, possibly caused by instabilities associated with destabilization in the ionization zones of the companion's envelope, as in dwarf novae.

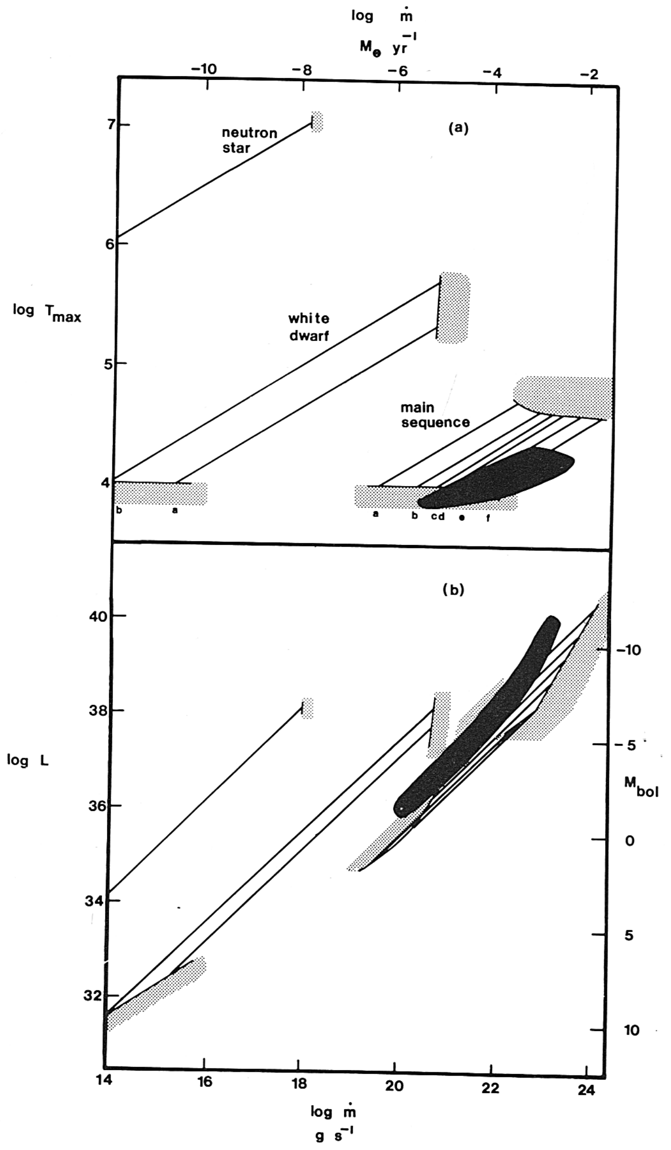

Figure 1. Variation of maximum disc temperature (Figure 2a) and disk luminosity (Figure 2b) with accretion rate. Accretion tracks are shown for 0.5(a), 1(b), 3(c), 9(d), 30(e) and 121(f) solar mass main sequence accretors. The region in which the accretion luminosity is less than the nuclear luminosity is indicated by heavy shading. At the upper boundary the disk luminosity is equal to the Eddington limit and the disk disrupts. At the lower boundary disk temperatures are less than ~ 10^4 °K and the disk becomes optically thin. Tracks for white dwarfs 0.4(a) and 1(b) $M_\odot$ and a neutron star of 1 $M_\odot$ are also shown.

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In the supercritical regime, at accretion rates ~ 10^{22} to 10^{24} g s^{-1} (depending on M_{MS}), the inner region of the disk is disrupted by radiation pressure. This leads to a fraction of the accreting gas being ejected in the form of an outflowing wind, which because of the low gravitational potential is likely to be optically thick. It will have the same general properties as the optically thick winds at Eddington luminosities that are generated in classical nova explosions. Increases in the mass ejection rate will produce expansion of the photospheric radius, a decrease of photospheric temperature and of the bolometric correction, and an increase in visual luminosity at approximately constant bolometric luminosity. The emission line spectrum will be replaced by an F or A absorption line spectrum similar to that observed in classical novae at maximum light. The rapid optical brightness changes of M33 Var A (Hubble and Sandage 1953) seem to agree with this interpretation.

One of the closest related stars in our own galaxy to the Hubble-Sandage variables is η Car. η Car exploded in the optical between 1836 and 1856, followed by a subsidiary outburst in 1889. In 1893 the spectrum was in absorption and early F. This was slowly replaced by the characteristic emission line spectrum with strong H, HeI, FeII and [FeII] (Humphreys 1975). The absolute magnitude at outburst was brighter than -11, and may have been as bright as -14 (Warren-Smith et al. 1979). At present the bulk of the emission is radiated in the infrared by a surrounding dust cloud, but the bolometric luminosity is still high, possibly still -14. All the characteristics are in agreement with that expected for a massive interacting binary which underwent a burst of accretion in the 19th Century. If correct the outburst of η Car was an accretion-driven nova explosion.

η Car is the only member of this class for which evidence of binary structure exists. Warren-Smith et al. (1979) find that the dust is concentrated in an annulus of size ~ 10^4 AU, and interpret this as evidence for binary structure. This is the first suggestion of binary structure in these variables. Binary periods must be greater than several days, most probably weeks to months. Doppler shifts will be small (orbital velocities ~ 10 km s^{-1}). They would not be detected through radial velocity changes but a search for eclipses with periods between several days and several months is an outstanding task with exciting prospects.

REFERENCES

Bath, G.T., Evans, W.D., Papaloizou, J. & Pringle, J.E. 1974, Mon. Not. R. astr. Soc., 169, 447.
Bath, G.T. Nature, submitted for publication.
Hubble, E. & Sandage, A. 1953, Astrophys. J., 118, 353.
Humphreys, R.M. 1975, Astrophys. J., 200, 426.
Humphreys, R.M. 1978, Astrophys. J., 219, 445.
Iben, I. 1965, Astrophys. J., 142, 993.
Rosino, L. & Bianchini, A. 1973, Astr. Astrophys., 22, 453.

Schwarzschild, M. & Härm, R. 1958, Astrophys. J., 128, 348.
Shakura, N.J. & Sunyaev, R.A. 1973, Astr. Astrophys., 24, 337.
Stothers, R. 1963, Astrophys. J., 138, 1074.
Warner, B. 1976, I.A.U. Symp. 73, Dordrecht: Reidel (eds. P. Eggleton, S. Mitton & J.A.J. Whelan), 85.
Warren-Smith, R.F., Scarrott, S.M., Murdin, P., & Bingham, R.G. 1979, Mon. Not. R. astr. Soc., 187, 761.