HYDROGEN DEPLETION AND THE EVOLUTION OF CATACLYSMIC VARIABLES TO LOW MASS X-RAY BINARIES

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ABSTRACT. Certain cataclysmic variables may evolve into low mass X-ray binaries if the white dwarfs can steadily accrete sufficient mass to exceed the Chandrasekhar limit. We present spectra of a recurrent nova and a low mass X-ray binary which are very similar to each other, and are also unusual for the strengths of the observed He II emission. We suggest that this similarity is not coincidental, but is evidence for an evolutionary link between the two classes of objects. A hydrogen depletion in the accreting gas is implied from the emission line fluxes, and may be an important parameter in determining whether accreted gas remains bound to the white dwarf, enabling eventual core collapse to occur.

1. INTRODUCTION

Considerable speculation has centered on the question of the possible evolution of nova systems to low mass X-ray binaries (LMXRBs). The cataclysmic variables (CVs) contain white dwarfs in mass exchange binaries, and if accretion onto the white dwarf occurs in such a way as to lead to a steady mass increase, the eventual collapse of the white dwarf is inevitable when its mass grows to exceed the Chandrasekhar limit. Several potential problems exist with this evolutionary scheme, however, which have raised doubts that it actually occurs. First, novae calculations have shown that accretion onto white dwarfs at rates typical of nova systems will cause recurring outbursts which lead to the ejection of most of, and perhaps even more than, the accreted mass. So, white dwarf masses could generally decrease because of accretion. Second, the collapse of white dwarfs has been studied as a cause of Type I supernovae, and the computations have shown that for most situations a detonation or deflagration wave results which completely disrupts the star, leaving no remnant (Nomoto 1982; Nomoto, Thielemann, and Yokoi 1984).

More recent calculations of outburst models for recurrent novae have shown that for certain parameters the mass ejected during outburst can constitute a small fraction (~10%) of the mass accreted, and so a

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gradual build-up in the mass of the white dwarf to 1.44 $M_\odot$ may be possible (Iben and Tutukov 1984). In addition, the fairly strong magnetic fields needed to explain the quasi-periodic oscillations in strong galactic bulge X-ray sources (van der Klis et al. 1985), together with the belief that such magnetic fields must decay on time-scales of $\sim 10^7$ yr, points to a formation for many of the LMXRBs which is recent, i.e., shorter than the time-scale over which the binaries would experience dynamical evolution (Taam and van den Heuvel 1986). Thus, the actual situation regarding the precursors of LMXRB systems is uncertain since theoretical arguments can be given both for and against white dwarf collapse in CVs from steady mass accretion. It is our purpose here to call attention to a similarity in the optical spectrum of a cataclysmic and a LMXRB which is sufficiently distinctive that we believe it argues for an evolutionary link between the two classes, with recurrent novae being the immediate precursors of some X-ray binaries.

2. OBSERVATIONS

We have obtained spectra of selected CVs and LMXRB systems as part of a program to identify suspected CNO lines in order to model the formation of emission lines in accretion disks. The spectra have been acquired with the CTIO 4m telescope and the RC Cassegrain spectrograph using the new 2D-Frutti CCD detector, and we show spectral scans of U Sco, a recurrent nova (Williams et al. 1981; Hanes 1985), and LMC X-2, a LMXRB (Bradt and McClintock 1983), in Figure 1. The spectrum of U Sco is distinct among CVs because no other object of this class has a He II line which is so strong with respect to either Hβ or the continuum. Spectroscopically, U Sco is much closer to the LMXRBs than to any of the CVs.

U Sco cannot be said to be typical of recurrent novae because this class of CVs is so disparate that no "typical" attribute can be ascribed to them other than that they all undergo occasional outbursts of some kind. Nor is there any apparent fundamental causal relationship between them, since some of the recurrents are believed to have outbursts powered by accretion episodes (Webbink 1976), whereas others have outbursts for which energy must be derived from thermonuclear reactions (Truran 1982). However, there are several recurrent novae in the thermonuclear runaway subclass, U Sco and T Pyx, which do have He II λ4686 emission stronger than Hβ. Warner (1976) has noted that classical novae tend to have detectable λ4686 emision, a spectroscopic feature which distinguishes them from dwarf novae. In this sense, then, the recurrent novae like U Sco and T Pyx may be a link between classical novae and the low mass X-ray binaries, for which the He II emission is usually the strongest spectral feature (Canizares, McClintock, and Grindlay 1979).

The only substantive difference between cataclysmic and X-ray binaries is the nature of the compact object: a white dwarf in the former and neutron star in the latter. It is known from studies of the spectra that the emission lines originate in the accreted gas which is transferred via Roche lobe overflow from the secondary stars to the degenerate primaries. The emission lines are formed in optically thin gas in the outer regions of accretion funnels or disks or in chromospheres which overlay the disks. The observed spectra of CVs and LMXRBs are similar to the extent that both are characterized by a flat continuum with superimposed line emission from H and He. There is, however, a systematic difference between the two classes of spectra: the LMXRBs have consistently stronger He II lines with respect to the Balmer lines than do the CVs (Bradt and McClintock 1983; Canizares, McClintock,

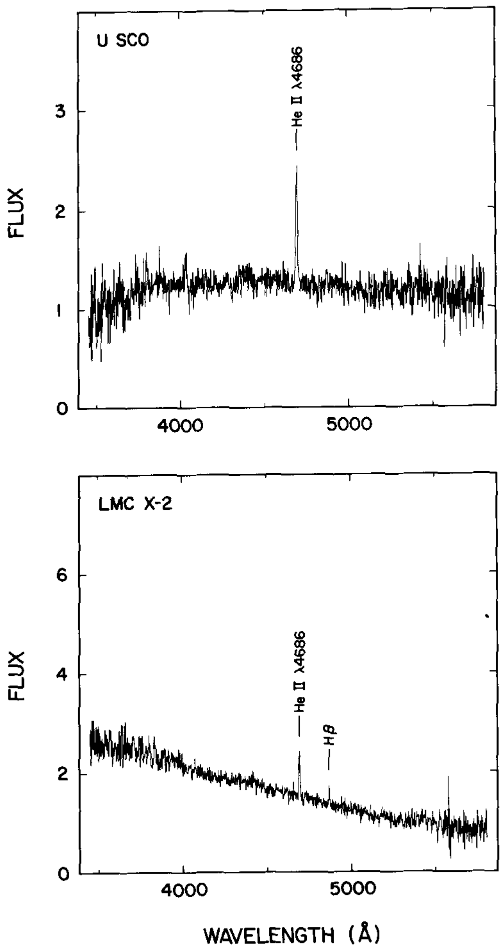

Fig. 1.- Spectral scans of the recurrent nova U Sco and the low mass X-ray binary LMC X-2. The only prominent emission line in either spectrum is He II λ4686. LMC X-2 also shows a weak Hβ emission feature. The spectra were obtained in July 1985 with the CTIO 4m telescope, and the units of flux are 10^{-16} erg cm^{-2} sec^{-1} A^{-1}.

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and Grindlay 1979; Williams 1983). In fact, the strength of the He II λ4686 emission compared to the other lines in many LMXRBs is unique among all objects except perhaps Wolf-Rayet stars, which are extremely helium-rich. It is this same feature in the spectrum of U Sco in having such predominant λ4686 emission which leads us to suspect that some recurrent novae and LMXRBs may be related through evolution.

3. DISCUSSION

The intensity of λ4686 with respect to Hβ is determined by the relative excitation conditions and He/H abundance. An approximate lower limit to the He/H abundance can be deduced from the line intensities because the excitation and ionization potentials are higher for He II λ4686 than for Hβ, and therefore all factors aside from the He/H abundance favor the production of the Balmer lines. If the lines are formed by recombination, as is likely because of their high excitation potentials, then the helium abundance is related to the line fluxes by the relation (Osterbrock 1974)

$$\frac{N(He)}{N(H)} > 0.08 \quad \frac{F(\lambda 4686)}{F(H\beta)}, \tag{1}$$

here the inequality is possibly very large because the differences in the excitation and ionization potentials of H and He are greater than 40 eV. The LMXRBs consistently have F(λ4686) > F(Hβ), and therefore an enrichment of He in the accreted gas from the secondary stars over the solar abundance is indicated for them. For a number of the known LMXRBs, e.g., LMC X-2, the He II line is substantially stronger than the Hβ emission, which is sometimes undetected, and this suggests that a high He/H ratio (He/H $\gtrsim$ 1) may be a common characteristic of the LMXRBs. This would be consistent with calculations for the "burst" sources, which are all low mass systems, which have shown that thermonuclear flashes of helium may be responsible for the brief, intermittent X-ray bursts (Joss and Rappaport 1984).

The fact that many of the LMXRBs probably have a large He/H ratio raises the possibility that this characteristic might be a parameter that is important for their formation. A straightforward reason exists why this condition should be important in allowing the evolution of CV white dwarfs to neutron stars. A sufficient requirement for matter accreting onto a white dwarf to remain bound to the star is that the gravitational binding energy of the material must be greater than the maximum energy released per gram in subsequent thermonuclear reactions. For a 1 $M_\odot$ white dwarf, the binding energy of surface material is 2 x 10^{17} erg/gr, and this value increases rapidly for higher masses because of the white dwarf mass-radius relation. By comparison, the conversion of H to He releases 6 x 10^{18} erg/gr, whereas the burning of He to C provides only 2 x 10^{17} erg/gr. Thus, if the accretion of normal H-rich material of solar composition occurs onto a white dwarf of mass M < 1.4 $M_\odot$, already very near the Chandrasekhar limit, the energy released during a nova outburst will probably lead to ejection of the accreted

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gas. However, a helium abundance of He/H = 2, which is roughly the limit that can be set for U Sco from the He II λ4686 intensity and the upper limit to Hβ, would require any gas accreted onto a star with $M \gtrsim 1.2\ M_{\odot}$ to remain bound to the star. The median mass of white dwarfs in cataclysmic systems is $< 1\ M_{\odot}$, (Robinson 1976), and thus a higher He/H abundance in the accreted gas dramatically increases the number of systems for which steady accretion to eventual core collapse can occur. We propose that hydrogen depletion of the mass transferring material in cataclysmic variables is an important condition which favors the evolution to LMXRBs, and is the cause of the accretion disks of the X-ray binaries being enhanced in helium. On the basis of the similarity of the spectrum of the recurrent nova U Sco to those of low mass X-ray systems, it is likely that some recurrent novae may be precursors to the LMXRBs. This possibility is given more credence by the recent outburst models for U Sco in which Starrfield, Sparks, and Truran (1985) propose a white dwarf mass for this system near $1.4\ M_{\odot}$.

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