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THE MYSTERY OF THE MISSING BOUNDARY LAYER

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ABSTRACT

The question of the nature of the ultraviolet and X-ray radiation field of cataclysmic binaries is addressed. The spectrum and luminosity of this radiation are important in determining the mass transfer rate and energy budget of the system and in studies of the ejecta surrounding novae. In many systems, the soft X-ray luminosity is $\sim 10^2$–10^4 times weaker than predicted by simple accretion models. We discuss several possible solutions to this discrepancy. The most likely are either that the optical luminosity of a typical old nova is produced partly by reprocessed ultraviolet light from the white dwarf, or that the boundary layer, where accreted matter settles onto the white dwarf, is both larger and more complicated than predicted by existing accretion disk models. The solution to this problem is of fundamental importance to accretion disk theory and will have implications for the study of most aspects of these systems, including models of the nova outburst itself.

Subject headings: stars: accretion — stars: binaries — stars: novae

I. INTRODUCTION

The classical novae are, of course, distinguished by their spectacular optical outbursts. The optical properties of these cataclysmic variable systems in their quiescent state have also been well studied. These observations have provided support for the standard model, in which mass is transferred from a low-mass main-sequence star onto its white dwarf companion. The matter spirals through an accretion disk and eventually settles onto the white dwarf, depositing the nuclear fuel that is later burned during the nova outburst. The gravitational potential energy released by the infalling matter is converted into the radiation that is seen during the quiescent phase.

In the context of this model, it is possible to determine the mass transfer rate, $\dot{M}$, from the total luminosity of the system. The accretion rate is an important parameter because it determines the period between outbursts, the violence of the outburst, and the mass and composition of the material returned to the interstellar medium. Current estimates of $\dot{M}$ are largely based on the optical luminosity. This often constitutes a small fraction of the total luminosity of the system since optical radiation is produced in the outer portions of the accretion disk where the matter still retains most of its gravitational potential energy. Radiation produced in deeper regions of the potential well is emitted predominantly as ultraviolet and X-radiation. This means that, energetically, it is possible for some stray component of optical light in the system to lead to a serious overestimate of $\dot{M}$. A measurement of the total optical, ultraviolet, and X-ray luminosity is necessary to obtain an accurate determination of the mass transfer rate.

Only recently, through the development of satellite-borne detectors, has it become possible to observe these systems in the near-ultraviolet and X-ray bands. Within the past 2 years, observations of a significant number of sources have been made in the soft X-ray range (Cordova, Mason, and Nelson 1981; Becker and Marshall 1981). These observations show that most old novae are soft X-ray sources with luminosities of $\sim 10^{30}$–10^{31} ergs s^{-1}. Near-ultraviolet observations (see Bath, Pringle, and Whelan 1980) are in general agreement with the standard accretion model.

Optical observations of shells of material surrounding old novae have indicated significant enhancements of CNO abundances (Williams *et al.* 1978). The interpretation of these observations is strongly dependent on the ionization of the shell, which in turn depends on the strength of the ionizing radiation. However, no observations are yet available of the energy band at 10–150 eV ($\sim$ 100–1000 Å), where the radiation field of many of these objects is expected to peak.

With this motivation we will consider the EUV and X-ray radiation produced by cataclysmic variables and its implications for models of these systems. In the next section we summarize the standard model for the accretion flow and indicate the sources of radiation that are present. In § III we apply this model to the soft X-ray observations and show that, particularly for the classical novae, the soft X-ray flux is much weaker than expected. This behavior has been recognized in certain systems

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(e.g., DQ Her; see Fabian, Pringle, and Rees 1976), but it is not generally recognized that this discrepancy is present in a broad class of cataclysmic variable systems. Some possible solutions of this problem are discussed in the last section.

II. STANDARD MODEL

In this section we present a simple model of cataclysmic variable systems and discuss the sources of EUV and X-ray radiation that are present in it. Such considerations have also beem summarized by Tylenda (1977) and Kiplinger (1979). We are especially interested in sources that produce significant emission over the interval covered by the IPC detector on board the *Einstein Observatory* (0.15–4.5 keV) since a large body of data on this type of close binary exists (see Cordova, Mason, and Nelson 1981; Becker and Marshall 1981; Becker 1981). After we present the simple model of the accretion flow, we discuss possible additional sources of radiation and the consequences of any breakdown of the simple model.

a) *Accretion Disk*

The fundamental source of energy in accreting systems is the release of graitvational potential energy as matter is transferred onto the surface of a white dwarf of mass M and radius $R_{\rm WD}$. The total luminosity released is $L_{\rm tot} = GM\dot{M}/R_{\rm WD}$. Roughly half of this energy will be released by the accretion disk, largely as optical and near-ultraviolet light. In steady state, the flux of radiation at any point in the disk is $F(r) = 3GM\dot{M}/8\pi r^3$ (for details, see Shakura and Sunyaev 1973; Pringle 1981). The temperature as a function of radius is set by equating this luminosity to the Planck function and follows the law

$$T(r) = T_*\left(\frac{r}{R_{\rm WD}}\right)^{-3/4},$$

where

$$T_* = 2.2 \times 10^5\left[\frac{\dot{M}}{10^{18}\ {\rm g\ s^{-1}}}\right]^{1/4} \times \left(\frac{M}{M_\odot}\right)^{1/4}\left[\frac{R_{\rm WD}}{5\times 10^8\ {\rm cm}}\right]^{-3/4} {\rm K}.$$

(see Bath, Pringle, and Whelan 1980). This temperature law changes in a complicated fashion for radii near $R_{\rm WD}$ because particle orbits become non-Keplerian (cf. Pringle 1981). The spectrum of the disk is set by integrating over the surface of the disk from its inner radius just above the white dwarf to its outer radius of approximately one-third the binary separation. Here we assume typical values of $M = M_\odot$, $R_{\rm WD} = 5 \times 10^8$ cm, and an outer radius of $R_{\rm out} = 10^{10.8}$ cm. Williams (1980) has shown that, for accretion rates which characterize classical novae ($\dot{M} \sim 10^{17}$–10^{18} g s^{-1}), the disk will be optically thick at its outer radius. The disk itself can be an important source of ionizing radiation for $\dot{M} > 10^{17}$ g s^{-1}, although it should not produce detectable soft X-ray emission. Most of the optical radiation comes from radii of the order of 10^{10} cm, well away from either edge of the disk.

b) *Boundary Layer*

The boundary layer marks the region where material stops circulating at the Keplerian angular velocity and settles onto the surface of the white dwarf (see Pringle 1977; Pringle and Savonije 1979). Unless the white dwarf is rotating near breakup, the total luminosity radiated by the boundary layer will be almost equal to that of the accretion disk (a consequence of virial equilibrium). Its spectrum is not well defined since it is influenced by such details as the presence of magnetic fields, obscuring gas in the system, and the area of the boundary layer. Pringle and Savonije (1979) have shown that, for accretion rates typical of classical novae ($\dot{M} \approx 10^{17}$–10^{18} g s^{-1}), boundary layer radiation will be thermalized and reradiated at a temperature set by both the total luminosity and the effective surface area of the region. The boundary layer has a thickness S which, as a first approximation, is comparable to the thickness of the disk at its inner edge. The surface area of the boundary layer is $2\pi S R_{\rm WD}$, and it covers a fraction $f = 2\pi R_{\rm WD} S/4\pi R_{\rm WD}^2 \approx 10^{-2.5}$ of the white dwarf surface. If this surface emits as a blackbody, the temperature of the boundary layer will be given by

$$T_{\rm BL} = 1.65 \times 10^5\left(\frac{M}{M_\odot}\right)^{1/4}\left(\frac{\dot{M}}{10^{18}\ {\rm g\ s^{-1}}}\right)^{1/4} \times \left(\frac{R_{\rm WD}}{5\times 10^8\ {\rm cm}}\right)^{-3/4} f^{-1/4}\ {\rm K}.$$

For reasonable values of the fraction of the white dwarf covered by the boundary layer ($f \approx 10^{-2.5}$, Pringle 1977), this region will make the dominant contribution to the EUV and X-ray radiation from the system.

The optically thick, boundary layer model outlined here is only strictly applicable for $\dot{M} > 10^{17}$ g s^{-1} (Pringle and Savonije 1979). At lower rates, the boundary layer may not be optically thick, and the radiation may not be thermalized. In this case, the actual X-ray flux will be larger than predicted because the accretion energy must be liberated as hotter, less efficient, bremsstrahlung radiation. This would only serve to strengthen our conclusions regarding the discrepancy between the observed and predicted X-ray emission reached below.

c) *Other Sources*

Several other sources of radiation are present in nova systems. The late-type companion can make a significant contribution to the near-infrared flux but is seldom detectable in the optical for classical novae (see Warner 1976). The white dwarf itself could contribute a significant amount of optical radiation in novae which are still burning (see the discussion by Truran 1982). However, the observation that old novae have nearly the same optical luminosity after as before an outburst (see McLaughlin 1960; Robinson 1975), and that nova light curves show the flickering which characterizes accretion-powered emission, both suggest that the white dwarf does not contribute much to the optical emission. A very hot white dwarf could, of course, dominate the far-ultraviolet and soft X-ray emission without producing much visible light.

The hot spot, where the accretion stream first strikes the disk, can produce both optical and ionizing radiation (see Warner 1974; Pringle 1977). This should be insignificant in comparison with the disk or boundary layer because the gravitational potential well is $\sim 10^2$ times deeper at the white dwarf surface than at the outer edge of the disk.

If the white dwarf has a strong magnetic field, the model we have presented above does not apply. The accretion disk will be disrupted at the point where the magnetic pressure first exceeds the ram pressure of the accreting gas (Lamb, Pethick, and Pines 1973). The source would then be similar to AM Her (see, e.g., Chiappetti, Tanzi, and Treves 1981); this may well be the case for DQ Her (see Ferland and Truran 1981). However, most of the classical novae do not show any of the characteristic properties of the AM Her stars and thus presumably have magnetic fields ($B \ll 10^7$ gauss) that have little influence on the flow.

III. COMPARISON WITH OBSERVATIONS

In this section we compare the predictions of the model outlined above to soft X-ray and optical observations. We consider first the case of the well-observed old nova V603 Aql. This system is a favorable object for study because it has a well-determined distance (380 pc, McLaughlin 1960) and white dwarf mass ($M = 0.9\ M_\odot$, Warner 1976), and is viewed nearly pole-on ($i = 15°$, Warner 1976; Slovak 1981). V603 Aql is the brightest old nova ($V = 10.8$ McLaughlin 1960) and its optical, ultraviolet, and X-ray spectra have been well studied (see Williams 1982; Ferland *et al.* 1982; Becker and Marshall 1981). The optical continuum has a luminosity of $10^{34.2}$ ergs s^{-1} which, in the model outlined above, implies a mass transfer rate of $\dot{M} = 10^{18.2}$ g s^{-1}. The boundary layer should radiate a soft X-ray luminosity of $L_x = 10^{34.5}$ ergs s^{-1} (Pringle 1977). For comparison, the observed soft X-ray luminosity is a factor of $\sim 10^{2.4}$ times smaller ($L_x = 1.3 \times 10^{32}$, Becker and Marshall 1981).

Conservation of energy demands that this missing energy be radiated in some other energy band since the gas must eventually come to rest on the white dwarf surface. Soft X-ray emission will be suppressed if the boundary layer is much larger than the fraction, $f \approx 10^{-2.5}$, of the white dwarf area suggested by Pringle (1977). In this case, the boundary layer could radiate the required energy at a lower temperature. If the boundary layer is large and cool enough, the bulk of the energy could lie in the unobservable far-ultraviolet.

As a test of whether this is a reasonable solution to the problems posed by the anomalous soft X-ray emission, and to check whether this syndrome affects other members of this class, we consider observations of a large number of classical and dwarf novae. We define a ratio, $L_x/L_{\rm opt}$, to be the energy flux observed by the *Einstein* IPC detector divided by the optical flux, λf_λ (5500 Å). The legend for Figure 1 lists the objects in the sample, which are taken from Cordova, Mason, and Nelson (1981) and Becker and Marshall (1981).

We compare these observations to the predictions of the standard model outlined above. As suggested by the discussion in § II, only the accretion disk and boundary layer need be considered since they dominate, respectively, the optical and soft X-ray emission. We allow two free parameters, the accretion rate and the fraction of the white dwarf surface covered by the boundary layer. The former sets the total luminosity of the system and the optical brightness, and both parameters affect the boundary layer temperature and soft X-ray flux. The white dwarf mass and radius are held fixed at the characteristic values of $M_{\rm WD} = 1.0\ M_\odot$ and $R_{\rm WD} = 5 \times 10^8$ cm respectively. The ratio $L_x/L_{\rm opt}$ is calculated by numerically integrating over the relevant energy distributions. For these calculations, we ignore orientation or aspect effects introduced by the inclination of the systems and average the radiation field over 4π steradians. This is proper because we wish to compare predictions with a sample of objects rather than with a specific case.

Figure 1 shows the results of these calculations. The horizontal axis is calibrated in both the mass transfer rate and the visible flux. There is a unique correlation between these two parameters in the context of the standard model because the boundary layer contributes little to the optical luminosity. The vertical axis is the ratio of soft X-ray to optical luminosity as defined above. Classical novae are plotted as diamonds and dwarf novae are shown as circles, and lines of constant relative-boundary-layer area f are drawn in the figure.

The one thing made clear by Figure 1 is that our understanding of the processes affecting soft X-ray emission is far from complete. In many cases (those in the lower right-hand corner of the figure), the dis-

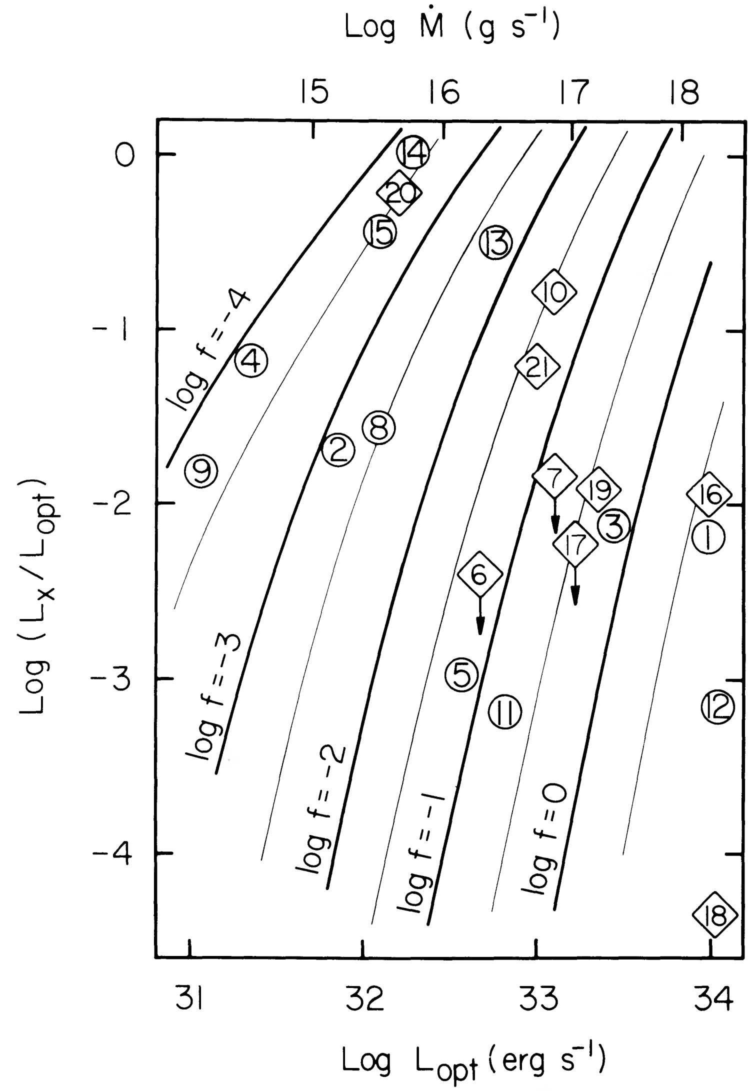

FIG. 1.—This figure shows the dependence of the ratio of soft X-ray to optical emission on the optical luminosity. Dwarf novae and classical novae are denoted by circles and diamonds, respectively, with arrows indicating upper limits. Luminosities are taken from Cordova, Mason, and Nelson (1981) and Becker and Marshall (1981). Lines of constant boundary layer fractional coverage of the white dwarf of radius 5×10^8 cm are shown, and the log of this fraction is marked at the lower end of the curves. The optically thick boundary layer model is not strictly appropriate for $\dot{M} \leq 10^{17}$ g s^{-1}, in which case even stronger X-ray emission is produced by the resulting hot bremsstrahlung source. (This effect may explain why several objects with low accretion rates lie above the line corresponding to the expected [−2.5] boundary layer.) Individual objects are: (1) TT Ari, (2) YZ Cnc, (3) T CrB, (4) U Gem, (5) AH Her, (6) DQ Her, (7) V533 Her, (8) VW Hyi, (9) EQ Mon, (10) GK Per, (11) KT Per, (12) CD −42°14462, (13) SS Cyg, (14) EX Hya, (15) 2A 0526−328, (16) V603 Aql, (17) T Aur, (18) V841 Oph, (19) RR Pic, (20) CP Pup, and (21) V1059 Sgr.

crepancy between the observed and predicted soft X-ray flux can be resolved only by artificially increasing the effective area of the boundary layer to a size several times larger than the entire white dwarf. Such a large area is inconsistent with the simple boundary layer model. Although these are extreme examples, few of the objects in Figure 1 lie near the line $f = 10^{-2.5}$ which represents the expected boundary layer (Pringle 1977). We also note that Cordova, Jensen, and Nugent (1981) inferred that the X-ray luminosity of the classical novae must be less than predicted by the standard model due to their failure to detect any classical novae in a *HEAO 1* X-ray survey.

IV. DISCUSSION

Possible solutions to the conundrum posed in the last section fall into two general categories; either the luminosity of the boundary layer has been overestimated, or the luminosity is correct and the boundary layer is able to radiate the required energy without producing the expected X-radiation.

The total luminosity of the boundary layer could have been overestimated because of any of several effects. For instance, if the white dwarf is rotating near breakup, material could settle onto the surface from Keplerian orbits at inner parts of the disk without releasing the stored kinetic energy (see Pringle 1981). Another possibility is that the parameters assumed for the white dwarf are very inaccurate. Both a much smaller mass and a much larger radius would be needed to produce the necessary suppression. Neither possibility seems very attractive.

Another interesting possibility is that the mass transfer rate for classical novae has been greatly overestimated. Classical novae are typically ~ 10 times brighter in visible light than are dwarf novae (see McLaughlin 1960; Payne-Gaposchkin 1957) and, according to the scenario outlined above, must transfer mass at an approximately 10 times faster rate. While the optical luminosities support this view, there is no great difference between the X-ray luminosities of the two classes (compare Cordova, Mason, and Nelson 1981 with Becker and Marshall 1981), suggesting similar accretion rates. A point in favor of this interpretation is that current models of the thermonuclear runaway which is believed to power the nova outburst do not produce explosions for accretion rates greater than 10^{18} g s^{-1} (Fujimoto 1982; Prialnik *et al.* 1982; MacDonald 1983). This solution introduces the ancillary problem of the origin of the bulk of the observed optical radiation from classical novae. Perhaps some model invoking far-ultraviolet radiation from a still burning white dwarf being reprocessed into the optical by the accretion disk could be made to work.

The second class of models to explain the missing soft X-rays are those which suppress X-ray emission from a boundary layer of the expected luminosity. A magnetic field and the accompanying cyclotron cooling provide an obvious explanation (see Fabian, Pringle, and Rees 1976), although the lack of the magnetic field signatures as seen in AM Her (see Schmidt, Stockman, and Margon 1981) presents a problem with this solution. Soft X-ray emission could also be suppressed if a great deal of absorbing gas is in the system. Ferland *et al.* (1982) considered the effects of the coronal gas in V603 Aql and found that the column density deduced from the emission measure would have little effect on the X-ray continuum from this nearly pole-on system (although they found that soft X-rays would be absorbed in edge-on systems such as DQ Her). Similarly, the interstellar medium column density of $\sim 10^{20}$ cm^{-2} to a typical nova should affect the observed X-ray luminosity by less than a factor of 2. None of these possibilities offers an attractive solution.

Another possibility is that the structure of the boundary layer is not as predicted by the standard model. The area of the boundary layer is set by the scale height of the disk at its innermost parts, and conditions here are affected by the viscosity law assumed (see Pringle 1981). If the assumed viscosity law is incorrect, and another pressure source increases the scale height of the disk by a large factor, the bulk of the boundary layer emission could be shifted into the unobservable far-ultraviolet. If this is correct, then for extreme cases, such as those of V603 Aql and V841 Oph, the boundary layer would actually be a halo surrounding the entire white dwarf.

The model for the accretion flow that we have presented assumes that the disk is in a steady state. If, instead, matter accumulated in the outer disk faster than it fell onto the white dwarf, the optical luminosity would be enhanced relative to the X-ray luminosity. Eventually, this matter must be dumped onto the white dwarf. This might correspond to a dwarf nova outburst, but the classical novae do not exhibit this type of behavior. Thus, departures from steady state flow are unlikely to provide a complete explanation for the discrepancy in the luminosity ratios.

We have called attention in this *Letter* to the fact that there exists an inconsistency between previous observational determinations of the relative optical and X-ray luminosities of classical nova systems and theoretical predictions of simple accretion models. While we have identified several possible sources of this discrepancy, it is clear that the solution to this problem is not yet at hand. We emphasize the potential importance of this finding with respect to our understanding of the nature of the outbursts of classical novae and the distinction between these and other classes of cataclysmic variables.

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