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# Accretion Disks in Supersoft X-ray Sources

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**Abstract.** We examine the role of the accretion disk in the steady-burning white dwarf model for supersoft sources. The accretion luminosity of the disk is quite small compared to the nuclear burning luminosity of the central source. Thus, in contrast to standard accretion disks, the main role of the disk is to reprocess the radiation from the white dwarf. We calculate models of accretion disks around luminous white dwarfs and compare the resulting disk fluxes to optical and UV observations of the LMC supersoft sources CAL 83, CAL 87, and RX J0513.9–6951. We find that if the white dwarf luminosity is near the upper end of the steady-burning region, and the flaring of the disk is included, then reprocessing by the disk can account for the UV fluxes and a substantial fraction of the optical fluxes of these systems. Reprocessing by the companion star can provide additional optical flux, and here too the disk plays an important role: since the disk is fairly thick, it shadows a significant fraction of the companion's surface.

## 1 Introduction

Supersoft sources have been modeled as white dwarfs accreting matter from a companion at a high enough rate to produce steady nuclear burning (van den Heuvel *et al.* 1992). In this model, accretion takes place through a disk; however, the total luminosity of the white dwarf due to nuclear burning is much greater than the total accretion luminosity of the disk. Thus it might appear that the disk is of little importance in supersoft systems - that it simply "adds fuel to the fire".

There is an important difference, however, between the disks in supersoft sources and ordinary accretion disks. In most accreting systems, the gravitational potential energy of the accreting material provides the main source of energy. In supersoft sources, the system's primary energy source is nuclear burning of the accreted material. A large fraction of the energy produced by nuclear burning irradiates the surface of the disk, and this exceeds the accretion energy dissipated in the disk by a large factor. Thus, in supersoft sources, the primary role played by the disk is to reprocess the copious radiation produced by the central source. The predominant role of reprocessing is a natural consequence of the steady-burning white dwarf model for these systems. It is a unique feature of supersoft sources which provides an opportunity to test both the model and our understanding of reprocessing in disks.

The plan of this paper is as follows: in §2 we show that nuclear-burning white dwarfs alone cannot provide the optical and UV fluxes observed in supersoft sources. We briefly describe our disk model in §3, and we show that simple accretion disks which do not include reprocessing also fall well short of the observations. We make our model progressively more realistic by including reprocessing of the white dwarf radiation by the disk, the effects of disk flaring, and other sources of reprocessed radiation in §4.1, 4.2, and 4.3, respectively.

Throughout the paper, we compare our model spectra to the observed optical and UV fluxes for three LMC supersoft sources: CAL 83, CAL 87, and RX J0513.9–6951. Sources in the LMC have the advantages of having a known distance and little extinction. These fluxes are approximate, and are shown in the figures as line segments. They are taken from the following sources: CAL 83 (UV) Bianchi & Pakull 1988; CAL 83 (optical) Smale *et al.* 1988; CAL 87 (UV) Hutchings *et al.* 1995; CAL 87 (optical) Pakull *et al.* 1988; RX J0513.9–6951 (UV and optical) Pakull *et al.* 1993. It is important to remember that all of these systems are variable, and that the optical and UV data for each system are not simultaneous. Of the three systems, CAL 83 probably provides the best comparison with models. RX J0513.9–6951 is a transient X-ray source which also shows substantial variability in the optical (Reinsch *et al.* 1996, Schaeidt 1996, and Southwell 1996). CAL 87 is an eclipsing system, and this presumably decreases its brightness and changes the shape of its spectrum (see contribution by Schandl *et al.* 1996a,b). Nonetheless, the available measurements give us a good idea of the fluxes from these systems.

## 2 Nuclear-Burning White Dwarfs

It is easy to see that a hot white dwarf alone cannot account for the very large optical and ultraviolet fluxes of supersoft sources. This is illustrated in Fig. 1, where we show blackbody spectra for 5 steady-burning white dwarfs which sit at the low-luminosity end of the steady-burning tracks calculated by Iben (1982). Their properties are listed in Tab. 1. We have scaled the spectra to a distance of 50 kpc. The resulting optical and ultraviolet fluxes are far smaller than those observed from CAL 83, CAL 87, and RX J0513.9–6951.

## 3 Simple Disk Models and Spectra

Can the disk provide the observed optical and UV flux? In order to answer this question, we model the disk in the following way. The radial structure of the disk is calculated using the "slim disk" equations. These were developed by Paczyński and collaborators to model disks around black holes (Paczyński & Bisnovatyi-Kogan 1981; Muchotrzeb & Paczyński 1982). They are a more sophisticated version of the standard thin disk equations in that they dispense with some of the simplifying assumptions made by the thin disk model, and allow a more accurate treatment of the disk, particularly in the boundary layer region near the accreting star. The radial disk equations are described in detail by Popham & Narayan (1995), who used them to model boundary layers in cataclysmic variables with high values of $\dot{M}$.

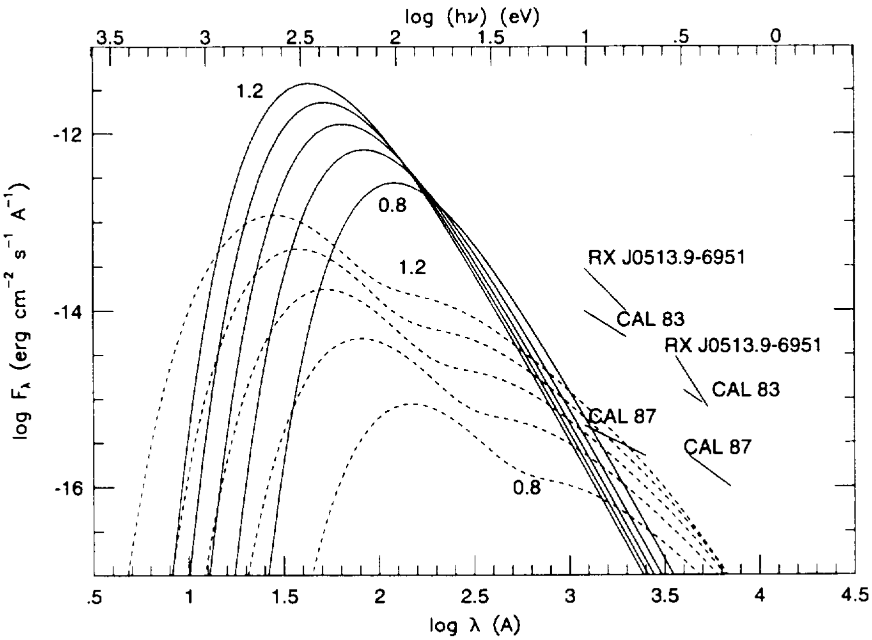


**Fig. 1.** Blackbody spectra of white dwarfs undergoing steady nuclear burning (solid lines), and of the corresponding accretion disks (dashed lines). The spectra are labeled by the white dwarf mass, and the white dwarfs sit at the lower limit of the steady-burning region, with parameters listed in Tab. 1. Observed optical and UV spectra of CAL 83, CAL 87, and RX J0513.9–6951(references in §1) are shown as line segments.

After calculating the radial structure of the disk, we calculate the vertical structure for each disk annulus. This involves solving the equations of hydrostatic equilibrium and simple two-stream radiative transfer equations, for values of the disk surface density, effective temperature and gravity given by the radial solution. We then use this vertical solution to calculate the continuum spectrum for that disk annulus. By adding the spectra of all of the annuli, we obtain the total disk spectrum.

We calculate the observed flux by simply dividing the luminosity by $4\pi d^2$, with $d = 50$ kpc. Note that the projected area of a flat disk varies with inclination as $\cos i$. The observed flux is often taken to be $F = L\cos i/2\pi d^2$, so that the flux integrated over a sphere of radius $d$ is $L$. Using this expression, our choice of $F = L/4\pi d^2$ corresponds to implicitly assuming that $i = 60°$. Note that the flux from a face-on disk is twice as large as this, $F(i = 0°) = L/2\pi d^2$.

How will the inclusion of the disk flux change the overall spectrum? The dashed lines in Fig. 1 show simple disk spectra for the same values of $\dot{M}$, $M_{\rm WD}$,

**Table 1.** Parameters for steady-burning white dwarfs and accretion disks at the low-luminosity edge of the steady-burning region (first five lines), and at a higher luminosity (last line).

| $M_{WD}$ $M_\odot$ | $\dot{M}$ $10^{-7}\,M_\odot\,yr^{-1}$ | $L_{WD}$ $10^{37}$ ergs $s^{-1}$ | $R_{WD}$ $10^{8}$ cm | $T_{WD}$ $10^{5}$ K | $L_{acc}$ $10^{35}$ ergs $s^{-1}$ |
|---|---|---|---|---|---|
| 0.8 | 0.51 | 1.53 | 25.3 | 2.41 | 1.36 |
| 0.9 | 0.85 | 2.53 | 15.7 | 3.47 | 4.08 |
| 1.0 | 1.27 | 3.82 | 11.3 | 4.53 | 9.47 |
| 1.1 | 1.82 | 5.44 | 8.78 | 5.61 | 19.1 |
| 1.2 | 2.50 | 7.48 | 7.14 | 6.74 | 35.3 |
| 1.2 | 4.98 | 14.9 | 18.4 | 4.99 | 27.2 |

and $R_{WD}$ as the nuclear burning white dwarfs. Note that two components are visible in the disk spectra: a hot component due to the boundary layer, and a cooler component due to the disk. Despite being less luminous overall than the white dwarfs, the disk spectra nevertheless dominate in the optical, and also in the UV for the higher values of $M_{WD}$. Nonetheless, they still fall well short of the observed fluxes from CAL 83 and RX J0513.9–6951.

## 4 Reprocessing Disks

The major role played by the disk in the steady-burning white dwarf model of supersoft sources is to reprocess the radiation from the white dwarf. This is a result of the huge luminosity of the white dwarf, which is $\sim 20-100$ times larger than the accretion luminosity for the parameters listed in Tab. 1. Adams & Shu (1986) calculated that 1/4 of the luminosity of the central star will hit the disk, assuming a flat, infinitely thin disk. Thus, the reprocessing luminosity should exceed the accretion luminosity by a large factor. We include the effects of this reprocessed luminosity in our disk spectra by changing the boundary condition at the disk surface in our vertical structure model to include the incident flux.

Another form of reprocessing is direct radiative energy flux across the star–disk boundary. It is less certain what fraction of the white dwarf luminosity will enter the disk in this way, but as a first estimate we simply take the fraction of the surface area of the star which is covered by the disk, which is given approximately by $H(R_{WD})/R_{WD}$, where $H$ is the disk height. This direct heating requires a change to the inner boundary condition on the radial radiative flux in our radial disk model.

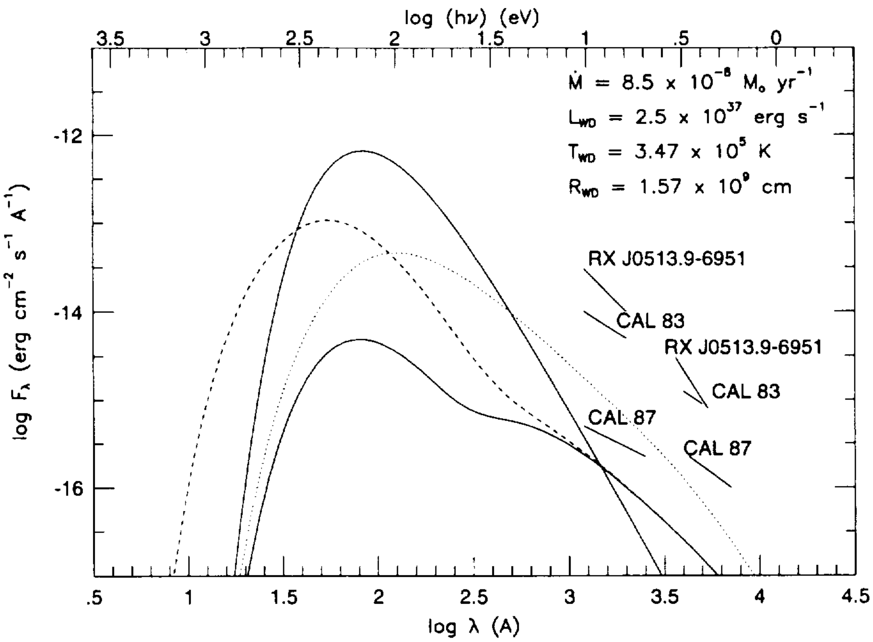


**Fig. 2.** Spectra of a disk with the $M_{WD} = 0.9\,M_\odot$ parameters listed in Tab. 1: spectra of the white dwarf and the disk with no external heating (solid lines), the disk spectrum including radiative heating through the disk–star boundary (dashed line), and the disk spectrum including the effects of reprocessing (dotted line).

### 4.1 Disk Spectra Including Reprocessing

Fig. 2 shows disk spectra using the parameters for $M_{WD} = 0.9\,M_\odot$ listed in Tab. 1. When direct heating through the star–disk boundary is included, the inner disk is much hotter, and the high-energy end of the spectrum is much brighter. However, the disk spectrum hardly changes in the optical and UV, since direct heating only affects the inner part of the disk.

Reprocessing, on the other hand, heats the entire disk surface, and produces a substantial increase of a factor of 3–5 in the optical and UV flux from the disk. Nonetheless, the fluxes still fall short of the observed ones by a factor of $\sim 10$. Thus, it seems clear that a substantially larger white dwarf luminosity will be required to explain the data. Accordingly, we take a white dwarf solution with $L_{WD} \simeq 1.5 \times 10^{38}$ ergs s$^{-1}$. The parameters for this solution are shown in the last line of Tab. 1. When reprocessing is included for this solution, we obtain the spectrum shown in Fig. 3. This comes much closer to the optical and UV data for CAL 83 and RX J0513.9–6951, but it still falls short by a factor of a few in the UV and a factor of 5–10 in the optical.

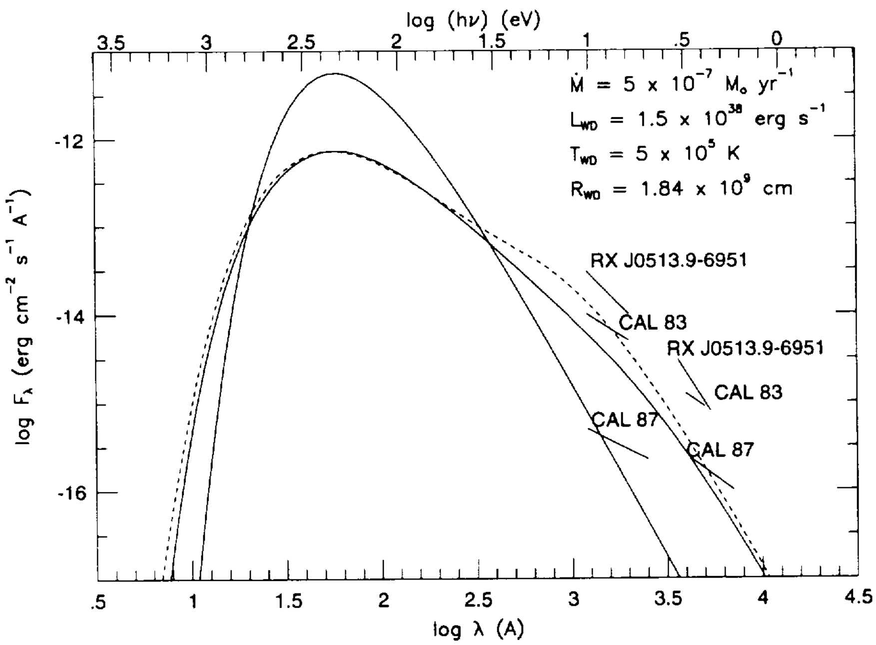


**Fig. 3.** Spectra of the steady-burning white dwarf and the disk including reprocessing (solid lines), and of the disk including reprocessing with disk flaring (dashed line), for a higher-luminosity solution with the parameters listed in the last line of Tab. 1.

## 4.2 Disk Flaring

Thus far we have calculated the flux incident on the disk surface by assuming a flat, infinitely thin disk. However, we can use our vertical structure code to compute the disk height $H(R)$. We find that the disk has a substantial thickness, with $H/R \gtrsim 0.25$. We also find that the disk surface is not flat; $d\ln H/d\ln R$, which is 1 for a flat disk with constant $H/R$, is $\simeq 1.1 - 1.15$ for the disk solution shown in Fig. 3. This increases the incident flux on the disk by a large factor, particularly in the outer parts of the disk.

The spectrum of the disk including the additional reprocessing flux due to flaring is shown by a dashed line in Fig. 3; the UV flux now is approximately the same as that of CAL 83, although it has a steeper slope. The optical flux still falls short of the observations. Note that the optical flux is constrained largely by the size of the disk; we have set the outer edge of the disk at $1.35 \times 10^{11}$ cm $\simeq 75 R_{\rm WD}$. This is slightly smaller than the Roche lobe radius of a $1.2\,{\rm M}_{\odot}$ star with a $2\,{\rm M}_{\odot}$ companion and a 1-day orbital period.

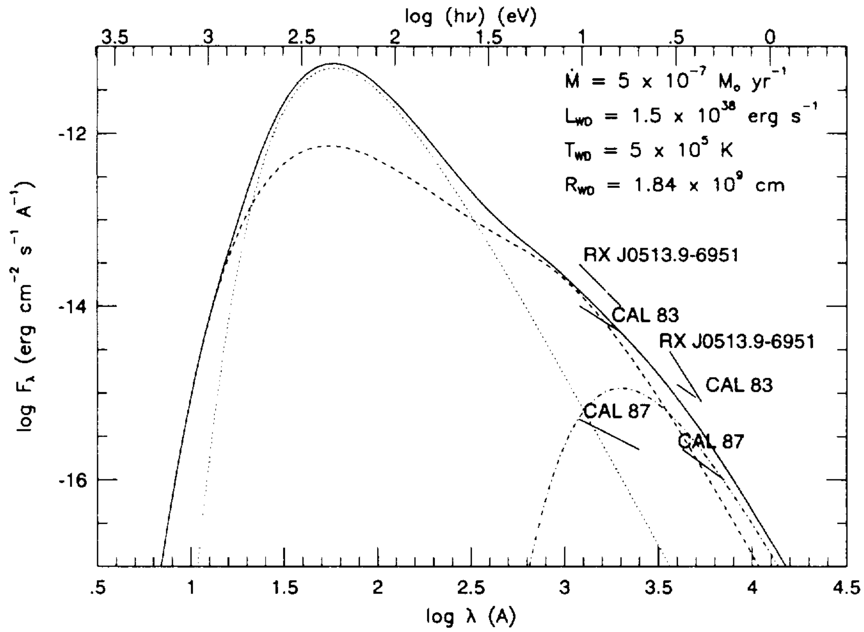


**Fig. 4.** Spectra for the same solution as in Fig. 3; the spectra of the white dwarf (dotted line), the disk with reprocessing and flaring (dashed line), and the donor star (dash-dotted line), and the combined spectrum of the three (solid line).

### 4.3 Other Sources of Reprocessed Radiation

Radiation from the white dwarf is also reprocessed by the donor star. Since the donor fills its Roche lobe, its radius expressed as a fraction of the binary separation $a$ depends only on the mass ratio. For a $2\,M_\odot$ donor and a $1.2\,M_\odot$ white dwarf, we find $R_{donor}/a \simeq 0.42$. We have done numerical integrations to determine the fraction $f$ of the white dwarf luminosity that reaches the donor surface. If no disk is present, $f$ is just the fraction of the total $4\pi$ solid angle which is subtended by the donor, so $f = 0.047$. However, a flat, infinitely thin disk prevents radiation emitted from the upper half of the white dwarf from reaching the lower half of the donor, and vice versa, reducing $f$ to 0.028. If the disk has a finite thickness, then some fraction of the donor surface is completely shadowed by the disk; for a disk with $H/R = 0.25$, $f = 0.0085$.

In the solution shown in Fig. 3, the disk height at the outer edge of the disk, taken from our vertical structure solution, corresponds to $H/R \simeq 0.275$, so that $f = 0.0071$. Despite this, reprocessing by the donor is still a significant source of flux from the system, particularly in the optical. Fig. 4 shows the spectrum of the white dwarf, the disk, and the donor star, assuming that the absorbed white dwarf luminosity is radiated evenly from the donor surface, and the combined spectrum of the three. The combined spectrum matches the observed UV and optical fluxes of CAL 83 fairly well. It falls short of the RX J0513.9–6951 fluxes by about a factor of 2, but reproduces the slopes quite well; however, as noted above, our model spectra would predict twice as much flux if viewed face-on. Our spectrum exceeds the CAL 87 fluxes, as expected since this system has a high inclination.

Additional optical flux may originate from the outer edge of the disk or from a region of increased disk height resulting from the impact of the accretion stream on the disk, as modeled in CAL 87 by Schandl *et al.* (1996).

## 5 Summary

We have examined the role of the accretion disk in supersoft X-ray sources, assuming that the steady-burning white dwarf model applies. Reprocessing of white dwarf radiation by the disk plays a uniquely important role in supersoft sources, and appears to be able to explain their large optical and UV fluxes. Our disk models also provide a foundation for more phenomenological models like the one by Schandl *et al.* (1996a,b), which agrees quite well with the lightcurve of CAL 87. In the near future we plan to use disk models in conjunction with evolutionary calculations (Di Stefano & Nelson 1996) to attempt to constrain $M_{\rm WD}$ and $\dot{M}$ in a number of close binary supersoft sources.

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