EFFECTS OF NUCLEAR BURNING ON X-RAY AND UV EMISSION FROM ACCRETING NONMAGNETIC DEGENERATE DWARFS

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INTRODUCTION

The energy liberated by nuclear burning of matter accreting onto degenerate dwarfs can be more than an order of magnitude greater than that available from the release of gravitational potential energy. Nuclear burning therefore significantly alters the characteristics of X radiation from such stars. Here we report the results of calculations in which steady burning occurs at the accretion rate, and compare them with our calculations (Kylafis and Lamb 1979, hereafter KL) which assumed no burning. These two studies illustrate the maximum and minimum effects of nuclear burning. Results for intermediate burning rates can be found by scaling from them.

In agreement with Katz (1977), we find that nuclear burning enhances the soft X-ray flux emitted from the stellar surface, increases Compton cooling of the emission region and therefore reduces the hard X-ray luminosity and softens the hard X-ray spectrum.

CALCULATIONS

Our calculations assume (1) steady, spherically symmetric accretion, (2) no magnetic field, (3) complete ionization of the accreting matter, and (4) steady nuclear burning at the accretion rate. Except for (4), these assumptions are the same as those of KL. The calculations we describe here neglect electron conduction and the possibility of differing electron and ion temperatures. Calculations which include electron conduction within a two-temperature treatment of the shock and emission region are underway (Imamura et al. 1979). They show that, while inclusion of these effects are needed for accurate results when burning occurs, the present calculations provide an excellent first approximation to them. In computing the nuclear energy generation rate, we assume that only hydrogen burns, and that the accreting matter has a composition of 70% hydrogen and 30% helium by mass. The other details of our calculations are the same as Kylafis (1978).

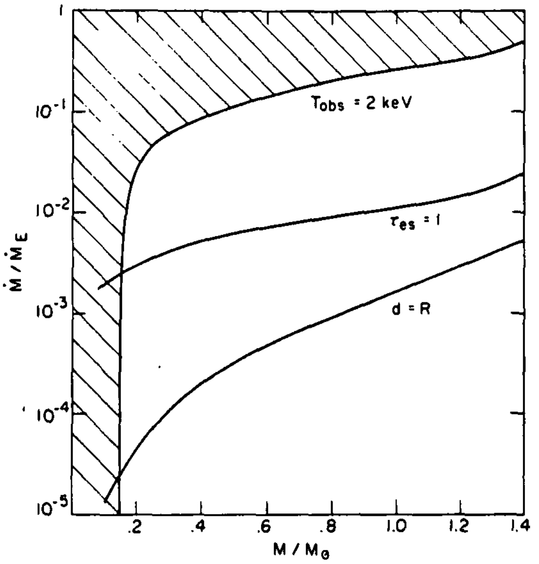

Fig. 1.- Parameter regimes in the (M, $\dot{M}$)-plane without nuclear burning. Below the curve labeled d = R, cooling of the hot, postshock matter as it reaches the stellar surface requires a shock standoff distance d > R; above the curve, d < R. Above the curve labeled T_{obs} = 2 keV, the temperature of the observed X-ray spectrum is less than 2 keV and the star ceases to be a hard X-ray source (shaded region).

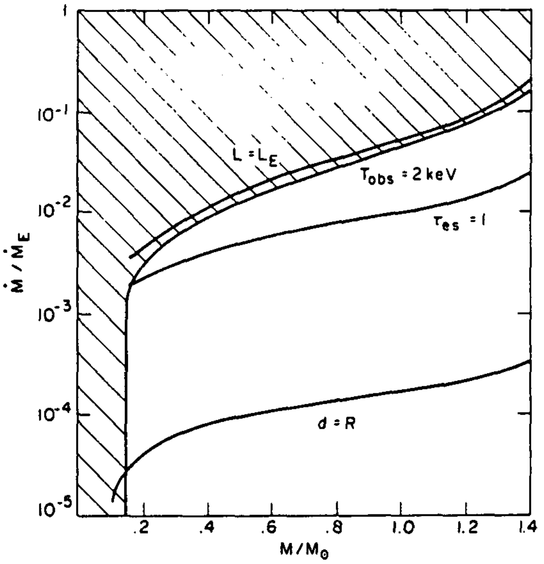

Fig. 2.- Parameter regimes in the (M, $\dot{M}$)-plane with nuclear burning. Above the curve labeled L = L_E, the luminosity from accretion plus nuclear burning exceeds the Eddington luminosity. The other curves have the same meaning as in Fig. 1.

With these assumptions, the following picture of X-ray emission by degenerate dwarfs undergoing nuclear burning emerges. As accreting matter flows toward the star, a strong collisional shock forms far enough above the star for the hot, postshock matter to cool and come to rest at the stellar surface (Hoshi 1973; Aizu 1973). Bremsstrahlung emission from the hot, postshock matter produces hard X rays. Roughly half of the X rays are emitted outward and form the observed hard X-ray flux; the other half are emitted inward and intercept the stellar surface, where they are reflected or absorbed. The blackbody flux resulting from the energy lost by the absorbed and reflected photons appears as UV and soft X radiation. The accreting matter does not burn in the hot X-ray emission region, but may do so deeper in the envelope of the star. The energy thus liberated is transported to the stellar surface and enhances the blackbody flux in soft X rays. Without burning, bremsstrahlung emission is the principal cooling mechanism in the X-ray emission region, except for high-mass ($M > 1\ M_\odot$) stars. With burning, Compton cooling by the intense soft X-ray flux dominates at all masses.

Figures 1 and 2 compare the parameter regimes encountered in accreting degenerate dwarfs with nuclear burning and without. In both cases the unit of accretion rate is the Eddington rate $\dot{M}_E = 4\pi\ cR/\kappa_{es}$ at which gravitational and radiation forces due to the accretional luminosity balance, assuming Thomson scattering. The corresponding unit of luminosity is $L_E = (GM/R)\ \dot{M}_E$, so that $L_{acc}/L_E = \dot{M}/\dot{M}_E$ where L_{acc} is the accretional luminosity. When nuclear burning occurs, there is an additional luminosity L_{nuc}. Above the curve labeled $L = L_E$ in

Figure 2, the sum $L_{acc} + L_{nuc}$ exceeds the Eddington luminosity. At low accretion rates, bremsstrahlung and Compton cooling are inefficient in removing the gravitational potential energy released by the infall of accreting matter and the shock stands at a large distance above the stellar surface (d >> R). Inward of the shock, the inflowing matter forms a hot, settling atmosphere in which most of the energy is liberated near the stellar surface (Fabian, Pringle, and Rees 1976; Katz 1977). As the mass accretion rate is increased, the shock moves in until eventually d = R. Comparison of the two figures shows that with burning the regime d < R extends to lower accretion rates. This is a result of the enhanced Compton cooling, which collapses the X-ray emission region. As the accretion rate is increased still further, the electron scattering optical depth from the emission region to infinity reaches unity ($\tau_{es} = 1$). Nuclear burning does not change the position of this curve. At higher accretion rates, the spectrum is severely degraded by Compton scattering. If the accretion rate is sufficiently high, the observed spectral temperature T_{obs} is less than 2 keV, and the star ceases to be a hard X-ray source. We note that with nuclear burning, radiation pressure, not Compton degradation, reduces the spectral temperature.

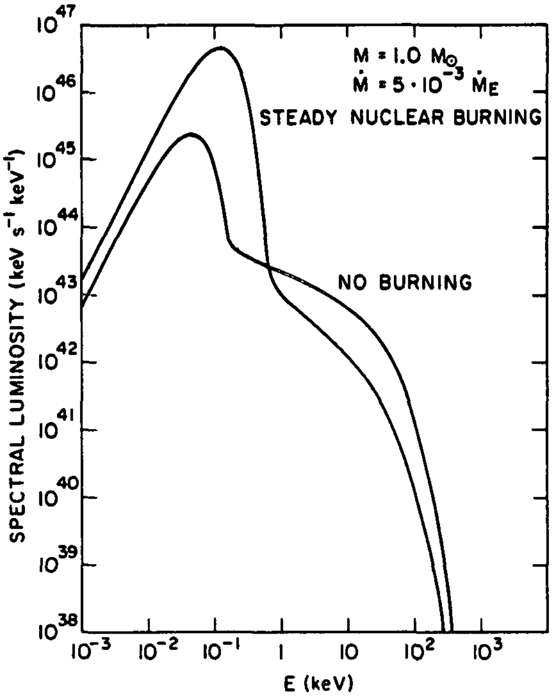

Fig. 3.- Comparison of X and UV spectra produced by accretion onto a 1.0 $M_\odot$ star at a rate 5×10^{-3} $\dot{M}_E$ with burning and without.

RESULTS

Figure 3 compares the X and UV spectra produced by accretion onto a 1.0 $M_\odot$ star at a rate 5×10^{-3} $\dot{M}_E$ with and without nuclear burning. This accretion rate corresponds to $\tau_{es} = 0.43$ and 0.46 in the two cases. The two spectra illustrate three important effects of nuclear burning: namely, the blackbody luminosity is greatly enhanced, the hard X-ray luminosity is greatly reduced, and the hard X-ray spectrum is softened.

The bremsstrahlung spectra observed at infinity have a hard (>2 keV) X-ray luminosity $L_h = 6.7 \times 10^{34}$ erg s^{-1} and 3.6×10^{35} erg s^{-1} in the two cases. A bremsstrahlung fit to the hard X-ray spectrum gives temperature T_{obs} = 12 keV and 25 keV. The blackbody component has a temperature T_{bb} = 0.043 keV and a luminosity $L_{bb} = 1.4 \times 10^{37}$ erg s^{-1} with burning, and T_{bb} = 0.016 keV and $L_{bb} = 2.8 \times 10^{35}$ erg s^{-1} without.

Figure 4 compares the correlations between T_{obs} and L_h for a 1.0 $M_\odot$ star, with burning and without. The accretion rate increases as one moves from upper left to lower right along the curves. The maximum observed temperature is about half as large and the maximum luminosity reached is nearly an order of magnitude less with burning than without. The maximum luminosities occur for $\tau_{es} \simeq 7$ and $\simeq 10$ in the two cases. Note that the curve of T_{obs} versus L_h is sharper in the case of burning. This is so because weakening of the shock by radiation pressure reduces T_{obs} in the case of burning, while Compton degradation is more important otherwise.

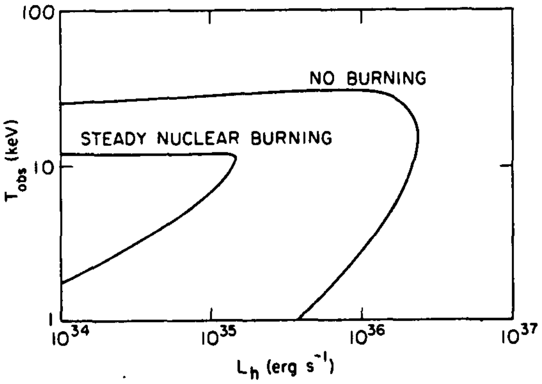

Fig. 4.- Comparison of the correlations between T_{obs} and L_h for a 1.0 $M_\odot$ star with burning and without.

DISCUSSION

Studies by Paczyński and Żytkow (1978), Sion, Acierno, and Turnshek (1978), and Sion, Acierno, and Tomczyk (1979) show the following behavior for degenerate dwarfs undergoing accretion. If the degenerate dwarf is initially hot, the hydrogen in the accreting matter soon ignites due to compressional heating. However, if the degenerate dwarf is initially cold and the accretion rate is not too high, the accreting matter becomes degenerate before it ignites. Electron conduction then transports energy into the core, and it must be heated before ignition can occur. Under these conditions, a long interval can elapse before nuclear runaway ensues. In either case, eventually there is a violent nuclear outburst (cf. Starrfield, Sparks, and Truran 1974).

Subsequent outbursts are separated by quiescent periods, in which nuclear burning occurs steadily at only a small fraction of the accretion rate. The quiescent periods are shorter for higher accretion rates. Depending on the accretion rate and the mass of the star, these periods can range from $>10^7$ yrs (Paczyński and Żytkow 1978) to $\simeq 20$ yrs or less (Sion et al. 1979). Nuclear burning has little effect on the mass-radius relation for high mass ($M > 1\ M_\odot$) stars, but appreciably increases the radius of lower mass stars if the accretion rate is high. For a narrow range of higher accretion rates, steady nuclear burning at the rate of accretion occurs (e.g. $1.0\text{-}2.7 \times 10^{-7}\ M_\odot\ yr^{-1}$ for a 0.8 $M_\odot$ star; Paczyński and Żytkow 1978). Still higher accretion rates lead to envelope expansion and the formation of a red giant with a degenerate core.

Earlier calculations (see KL and references therein) have explored X-ray emission by degenerate dwarfs in the absence of nuclear burning. These calculations apply to the epoch before an initial outburst and to the intervals between outbursts, if little burning occurs during them. The calculations we have described here (see also Katz 1977) apply directly to the state of steady nuclear burning that occurs for a narrow range of high accretion rates. By scaling, they can also be used to estimate the behavior between outbursts when appreciable burning occurs. In both cases, account must be taken of the larger radii that result from burning. Of course, X-ray emission will be overwhelmed by the outbursts themselves and will cease if the star becomes a red giant.

Our calculations show that the characteristics of accreting non-magnetic degenerate dwarfs undergoing significant nuclear burning are (1) a luminosity in soft X-rays that can often be 100 times the hard X-ray luminosity, (2) a hard X-ray luminosity nearly an order of magnitude less than in the absence of burning, and (3) a softer X-ray spectrum, with temperatures as low as ≈10 keV for a 1 $M_\odot$ star even in the absence of degradation due to Compton scattering.

Our results can be applied directly to the many cataclysmic variables which are now known to be X-ray sources, such as SS Cyg, U Gem, and EX Hya, if they accrete radially. If disk accretion occurs, measurement of the soft X-ray flux may still constrain the amount of steady nuclear burning that can be taking place. Our results can also be applied to low mass X-ray binaries, such as Cyg X-2, if they are degenerate dwarfs (Branduardi et al. 1979).

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