TWO-FLUID CALCULATIONS WITH CONDUCTION OF X-RAY EMISSION FROM ACCRETING NONMAGNETIC DEGENERATE DWARFS

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INTRODUCTION

Kylafis and Lamb (1979, hereafter KL) have recently completed a comprehensive study of X-ray emission from accreting nonmagnetic degenerate dwarfs. Their calculations assumed a common temperature for the electrons and the ions, and neglected electron conduction. However, when Compton cooling of the X-ray emission region becomes important at high masses, electron conduction begins to play a role (Kylafis 1978).

Here we report the results of calculations which allow the temperatures of the electrons and the ions to differ and which include electron conduction. We confirm that such a treatment is required for accurate results whenever Compton cooling greatly dominates bremsstrahlung cooling in the emission region. With no nuclear burning, Compton cooling dominates in a small region of parameter space (Katz 1977, KL). We find that two-fluid calculations are needed only in the smaller region defined by $M \gtrsim 1.2\ M_\odot$ and $\dot{M} \gtrsim 10^{-2}\ \dot{M}_E$, where $\dot{M}_E$ is the accretion rate at which gravitational and radiation forces balance. Thus the approach of KL, who considered this case, is justified. With nuclear burning, however, Compton cooling dominates throughout most of parameter space (Katz 1977, Weast et al. 1979). We find that two-fluid calculations are then needed when $M \gtrsim 0.4\ M_\odot$ and $\dot{M} \gtrsim 10^{-4}\ \dot{M}_E$.

Our results show that the X-ray spectrum is softer but the X-ray luminosity is larger when a two-fluid treatment is used. However, the changes are generally $\lesssim 25\%$. Electron thermal conduction is less important than one might expect. We illustrate these points by comparing the results of one- and two-fluid calculations for a $1.4\ M_\odot$ star accreting at a rate of $0.3\ \dot{M}_E$ without nuclear burning.

CALCULATIONS

Our calculations assume (1) steady, spherically symmetric accretion, (2) no magnetic field, (3) complete ionization of the accreting matter,

and (4) either no nuclear burning, or steady burning at the accretion rate. These assumptions are the same as those of KL and Weast et al. (1979). However, here we allow for differing electron and ion temperatures and include electron conduction.

With these assumptions, the following picture of X-ray emission by degenerate dwarfs emerges. Matter freely falling from infinity forms a standoff shock above the stellar surface (Hoshi 1973, Aizu 1973). The shocked plasma has a temperature of 10^8-10^9 K and emits X-rays, due to thermal bremsstrahlung, as it cools and settles onto the stellar surface. Roughly half of the X-rays are emitted outward and produce the observed hard X-ray flux; the other half are emitted inward and intercept the stellar surface, where they are reflected or absorbed. The resulting blackbody flux from the stellar surface appears as UV and soft X-radiation. Without nuclear burning, the postshock plasma cools by thermal bremsstrahlung except for high-mass ($M \gtrsim 1 M_\odot$) stars where Compton cooling by the blackbody flux dominates. With nuclear burning, the blackbody flux is much larger and Compton cooling dominates for all masses.

In either case, when Compton cooling is very large, the Compton cooling time scale may be less than the electron-ion energy exchange time scale. The electrons are then cooled so rapidly that they are unable to achieve a common temperature with the ions. The rapid Compton cooling also reduces the standoff distance of the shock. The electron temperature gradient increases and electron conduction becomes significant. Under these circumstances, accurate results require a two-fluid treatment with conduction of the X-ray emission region.

So far, we have implicitly assumed that the shock is produced by Coulomb collisions. This assumption is not as critical as one might suppose. Provided the shock does not convert a significant amount of energy into waves or nonthermal particles, the structure of the emission region and the resulting X-ray spectrum are not sensitive to the jump conditions at the shock. We have demonstrated this by computing two-fluid models without conduction in which we assumed that the ratio β of the electron and ion temperatures just behind the shock equaled 1 and 1/1836. The spectra in the two cases were nearly identical. The spectral fluxes differed by only 3% at 200 keV and by less than a factor of 4 even at 1 MeV.

Our calculations are carried out as follows. We use the Chandrasekhar mass-radius relation for degenerate dwarfs, and assume a composition $X = 0.7$, $Y = 0.3$ for the accreting plasma. We determine the temperature and density structure of the emission region by imposing the two-fluid jump conditions (Shafranov 1957) at the ion shock, and integrating the two-fluid hydrodynamic equations inward subject to the boundary conditions $v = v_{ff}$, $T_i = T_e = 0$, $J = 0$ at $r \gg R$ and $v \to 0$, $T_i = T_e = T_{bb}$, $J = 0$ at $r = R$, where v_{ff} is the freefall velocity, T_i and T_e are the ion and electron temperatures, T_{bb} is the stellar blackbody temperature, and J is the conductive flux. Radiation pressure is taken into account. Bremsstrahlung, Compton cooling, and conduction are included in the emission region. Iterations are performed until a self-consistent value for the Compton cooling rate is obtained. We use a Monte Carlo technique to treat degradation of the X-ray spectrum and the albedo of the stellar surface (Kylafis 1978).

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Our results show that the choice of boundary condition J = 0 at
r = R is supported by several physical arguments. This effectively
rules out the possibility suggested by Fabian, Pringle and Rees (1976)
and invoked by King and Lasota (1979) of solutions in which conduction
transports most of the accretional energy into the star, quenching
much of the hard X-ray emission.

RESULTS

Figures 1-3 show the structure of the emission region for a 1.4 $M_\odot$
star accreting at a rate of 0.3 $\dot{M}_E$ without nuclear burning.[1] The
accretion rate corresponds to an electron scattering optical depth
τ_{es} = 14 from the emission region to infinity. This model shows the
largest difference in electron and ion temperatures and the largest
conductive flux that we find assuming no nuclear burning. As such
it represents an extreme case, but it is typical of what we find if
there is burning.

Figure 1 compares the temperature profile in the emission region
of the one-fluid calculation with those of the two-fluid calculation.
The standoff distance of the shock in the former case is 8.9 x 10^5 cm
and in the latter 1.1 x 10^6 cm. In the one-fluid calculation, the
shock temperature T_s = 196 keV (2.3 x 10^9 K) whereas the electron and
ion temperatures just behind the ion shock in the two-fluid calculation
are T_e = 97 keV and T_i = 336 keV.

Figure 2 and 3 show the thermal bremsstrahlung and Compton cooling
rates in the emission region of the two-fluid calculation. Figure 2
also shows the enthalpy and conductive fluxes F_H and J, whereas Figure
3 also shows the divergences of these fluxes $\nabla \cdot F_H$ and $\nabla \cdot J$. Compton
cooling clearly dominates throughout most of the emission region.
The ratio of F_H and J is a measure of the relative importance of con-
duction, and shows that it is significant throughout the emission
region but never dominates. The value of F_H ahead of the electron pre-
cursor represents the kinetic energy of the freely falling plasma.
Since J = 0 ahead of the precursor and J = F_H = 0 at the stellar surface,
conduction and bulk motion only transport energy from one part of the
emission region to another, whereas thermal bremsstrahlung and Compton
cooling represent real energy losses. Nevertheless, Figure 3 allows us
to compare the local heating and cooling due to the former with the
cooling due to the latter. Note that $\nabla \cdot F_H$ and $\nabla \cdot J$ are zero in front of
the precursor and at the stellar surface.

On the basis of the temperature profiles shown in Figure 1, the
emission region can be conveniently divided into three parts: (A) a
precursor or preshock region, (B) a two-temperature ($T_e \neq T_i$) region,
and (C) a single-temperature ($T_e \simeq T_i$) region. The electron temperature
in region A is nearly equal to its postshock value due to thermal
conduction. However, the electron denisty here is relatively low and
very little thermal bremsstrahlung and Compton cooling takes place.
This region therefore has little effect on the postshock structure or
on the X-ray spectrum that is produced.

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[1]We inadvertantly omitted radiation pressure from this particular calculation. If includ-
ed, it would reduce the one-fluid shock temperature T_s and the two-fluid ion shock tempera-
ure T_i by 30%, thereby altering other quantities by similar amounts. Quantitative compari-
sons between the results for the one- and two-fluid calculations should still be valid.
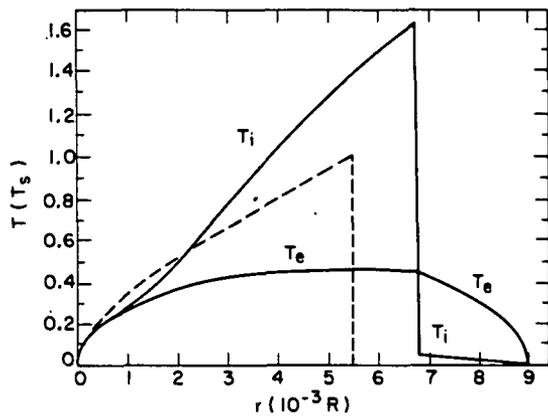
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Fig. 1.- Comparison of temperature profiles
in the X-ray emission region of a 1 M$_{\odot}$ star
accreting at a rate 0.3 $\dot{M}_E$ without nuclear
burning. The dashed curve shows the temp-
erature profile in the one-fluid calcula-
tion, and the solid curves labeled T$_e$ and
T$_i$ show the electron and ion temperature
profiles in the two-fluid calculation. The
temperatures are in units of the one-fluid
shock temperature T$_s$ = 2.3 x 10^9 K and the
height r above the stellar surface is in
units of the stellar radius R = 1.6 x 10^8
cm. The emission region can be convenient-
ly divided into three parts: (A) a pre-
shock region, (B) a two-temperature (T$_e$ ≠
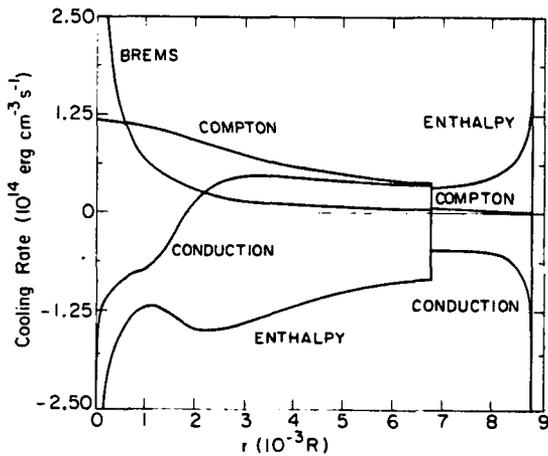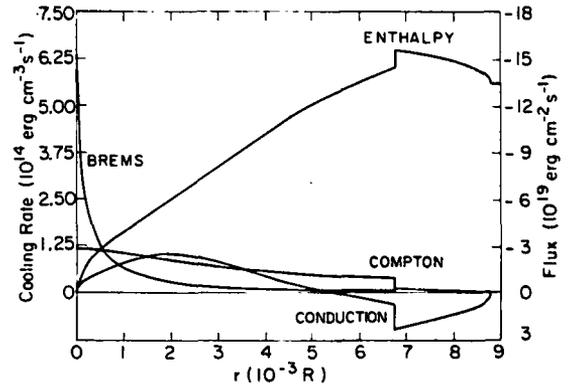T$_i$) region, and (C) a one-temperature
(T$_e$ = T$_i$) region.

Fig. 2.- The thermal bremsstrahlung and
Compton cooling rates, and the enthalpy
and conductive fluxes F$_H$ and J in the
X-ray emission region of the two-fluid
calculation shown in Fig. 1. Positive
values of the rates correspond to cooling,
negative values to heating; positive flux-
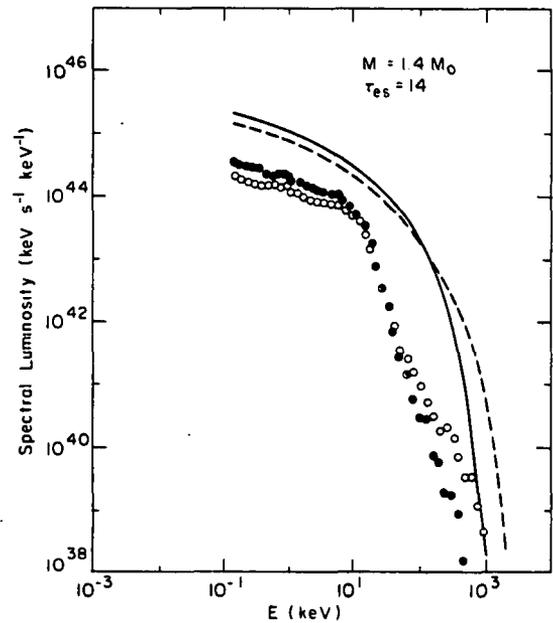es are directed away from the star, nega-
tive toward it.

Fig. 3.- The thermal bremsstrahlung and
Compton cooling rates, and the divergen-
ces ∇·F$_H$ and ∇·J of the enthalpy and con-
ductive fluxes in the X-ray emission re-
gion of the two-fluid calculation shown
in Fig. 1. Positive values correspond to
cooling, negative values to heating.

Fig. 4.- Comparison of the hard X-ray spec-
tra produced by the one- and two-fluid cal-
culations shown in Fig. 1. Key: ------
spectrum produced in the emission region,
o o o degraded spectrum observed at infin-
ity in the one-fluid calculation; ———
spectrum produced in the emission region,
● ● ● degraded spectrum observed at infin-
ity in the two-fluid calculation.

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Although region B comprises most of the emission region, very few X-rays are produced in this region because bremsstrahlung emission is dominated by both Compton cooling and conduction (see Figure 3). The electron temperature here is determined by the balance between ion heating, and Compton and conductive cooling. These processes are independent of T_i, and hence β. The structure of the emission region and the resulting X-ray spectrum are therefore insensitive to the value of β, as we demonstrated earlier. The value of the electron temperature just behind the shock is $\simeq$ half that in the one-fluid calculation (see Figure 1). This has several consequences. The Compton cooling rate is smaller (2.6×10^{37} erg s^{-1} versus 3.0×10^{37} erg s^{-1}) and the thickness of the emission region is therefore about 20% larger. The lower temperature and the larger emission region reduce the temperature gradient so that conduction is less important than one might expect. Lastly, fewer hard X-rays are produced by the star because the maximum electron temperature in the emission region is smaller.

Thermal bremsstrahlung is larger than Compton cooling in region C and the bulk of the X-rays are therefore produced here. Because conduction transports energy from region B, where Compton cooling dominates, to region C, where thermal bremsstrahlung dominates, 30% more X-rays are produced in the two-fluid calculation (1.7×10^{37} erg s^{-1} compared to 1.3×10^{37} erg s^{-1}). Since conduction deposits energy in the coolest region near the stellar surface, the resulting X-ray spectrum is softer.

Figure 4 compares the X-ray spectra produced in the one- and two-fluid calculations. The spectrum produced in the emission region is softer in the two-fluid calculation: the spectral flux is 50% larger at 10 keV, and factors of 2 and 400 smaller at 200 keV and 1 MeV. As this X-ray spectrum passes through the accreting plasma above the shock, it is degraded by Compton scattering. Figure 4 also compares the degraded X-ray spectra which are observed at infinity. The degraded spectra are little different, a bremsstrahlung fit giving an observed temperature T_{obs} = 10 and 8 keV in the one- and two-fluid cases. Both degraded spectra show a power law tail, but the softer initial spectrum in the two-fluid calculation essentially eliminates the further high energy excess which was present in the degraded spectrum in the one-fluid calculation. Since the example illustrated represents the most extreme case when there is no nuclear burning, and the typical case when there is burning, we conclude that the changes are generally $\leq 25\%$. The dramatic spectral variations and the correlation between T_{obs} and L_h reported by KL are little changed, and similar behavior should occur when there is nuclear burning (Weast et al. 1979).

In summary, we find that a two-fluid treatment including conduction is required for accurate results whenever Compton cooling greatly dominates bremsstrahlung cooling in the emission region. The X-ray spectrum is softer but the X-ray luminosity is larger when a two-fluid treatment is used. However, the changes are generally $\leq$ 25%. Electron thermal conduction is less important than one might expect.

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