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THERMONUCLEAR FLASH MODEL FOR LONG X-RAY TAILS FROM AQUILA X-1[1]

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ABSTRACT

The prolonged phase of X-ray emission lasting ~ 2500 s after an X-ray burst event in the recurrent transient Aql X-1 is interpreted as an extended phase of hydrogen burning in the accreted envelope of a neutron star. The nuclear burning is accelerated by electron capture processes at the high densities ($\sim 10^7$ g cm^{-3}) characteristic of the accreted layer. In this model, the extended phase of nuclear burning is due to the fact that the envelope is out of thermal equilibrium. Therefore only the first X-ray burst emitted by Aql X-1 during its transient outburst exhibits a long X-ray tail. In contrast, the properties of the subsequent bursts are distinguished by a lack of an X-ray tail reflecting the much smaller accumulated masses which result from the effects of thermal inertia in the neutron star envelope. The characteristics of the latter bursts are similar to those of typical X-ray bursters. For a neutron star characterized by a mass and radius of 1.4 $M_\odot$ and 9.1 km, respectively, the occurrence of the long X-ray tail requires that the mass of the accumulated layer $\sim 10^{23}$ g and the envelope temperatures of the neutron star be less than 1.5×10^7 K. This interpretation is found to be consistent with the thermal relaxation of the neutron star envelope during the quiescent state of Aql X-1 and with the mass accretion rates inferred for the transient outburst itself.

Subject headings: radiation mechanisms — stars: individual (Aquila X-1) — stars: neutron — X-rays: bursts — X-rays: stars

1. INTRODUCTION

It is generally well accepted that X-ray bursts result from a thermonuclear shell flash instability in the accreted hydrogen-helium–rich layers on the surface of neutron stars in close binary systems (Joss & Rappaport 1984; Taam 1985). Although the gross characteristics of the observed bursts can be understood within the general framework of such a model, a number of discrepancies still remain upon detailed quantitative comparisons between observation and theory. Among them is the observation by Czerny, Czerny, & Grindlay (1987) of a unique X-ray burst in the recurrent soft X-ray transient source Aql X-1. During its 1979 March and April outburst two type I X-ray bursts were detected during its decay phase. The characteristic which distinguished the first X-ray burst (seen at least 9 days after the maximum peak of the outburst) from typical X-ray bursts observed from other sources was the discovery that it exhibited an extremely long, relatively flat, X-ray tail. This prolonged phase of X-ray emission lasted for more than 2500 s after the burst maximum with the flux exceeding the pre–X-ray burst level by more than 25%. A second burst was observed 4 days later when the persistent emission from the source was a factor of 2 lower. The luminosity profile of the latter burst was similar to typical X-ray bursts; however, it, too, exhibited a tail, but much less pronounced than in the first burst observed. Although the peak burst luminosity was similar to that of the first burst, an enhancement of only 7% was visible 500 s after the burst. For both bursts, the peak burst luminosities are likely to be less than the Eddington limit since there is no evidence for radius expansion of the neutron star. In addition, the obervations of Koyama et al. (1981) of two X-ray bursts seen in the 1980 May outburst indicate peak burst fluxes larger than those observed by Czerny et al. (1987) by a factor of 1.4.

We have reexamined the origin for the extended X-ray tails in terms of the thermonuclear flash model. Of central importance to our interpretation is that the first X-ray burst observed by Czerny et al. (1987) was the first burst emitted from the neutron star in the 1979 March and April outburst. The properties of such an X-ray burst are expected to depart significantly from bursts calculated under steady state thermal conditions where a limit cycle behavior is achieved (see, for example, Fujimoto, Hanawa, & Miyaji 1981; Hanawa & Fujimoto 1982). Such a state is not expected to be reached especially for the X-ray bursts produced during the initial stages of the transient outburst event (Fushiki & Lamb 1987). For a similar interpretation for the precursor to the outburst of Cen X-4 (Belian, Conner, & Evans 1972), see Hanawa & Fujimoto (1986).

The observations of Czerny et al. (1987) indicate that the flux in the quiescent state is about a factor of 440 times lower than the maximum persistent flux in the outburst state. Furthermore, the study by Kaluzienski et al. (1977) suggests that the inactive phase lasts for a period of 12–16 months. Therefore, it is likely that the envelope of the neutron star in Aql X-1 (and probably in other recurrent soft X-ray transient sources as well) is characterized by low temperatures ($\sim 10^7$ K). In this paper we report on the results of detailed numerical calculations of X-ray bursts emitted from such accreting neutron stars. We find that the prolonged X-ray tail can be understood in terms of an extended phase of hydrogen burning at high density ($\rho \sim 10^7$ g cm^{-3}) accelerated by electron capture processes. Hence, the presence of such tails offers a possible diagnostic probe of the physical conditions in the nuclear-burning regions of the neutron star envelope. In the next section we present the results of the detailed calculations for a series of X-ray bursts. The implications of the results as applied to Aql X-1 are discussed in the final section.

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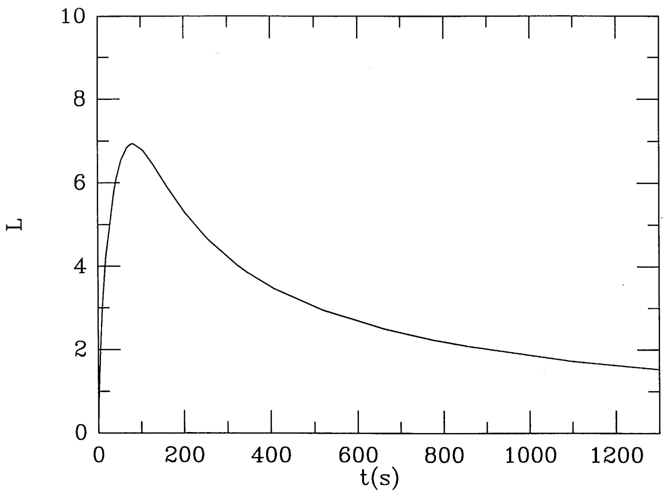

FIG. 1*a*

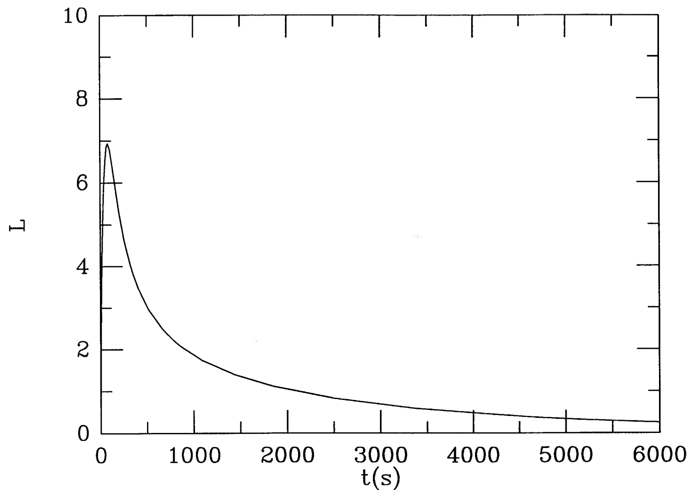

FIG. 1*b*

FIG. 1.—The luminosity profile of the first X-ray burst produced after the onset of accretion for the case corresponding to $T_b = 10^7$ K. The luminosity, L, is in units of 10^{37} ergs s^{-1}. In (*a*) the detailed profile during the burst rise can be seen. In (*b*) note the long relatively flat X-ray tail extending out to 6000 s.

2. RESULTS

The construction of the initial model and the evolution of the accreted layers on the neutron star surface were followed with the KEPLER computer code modified to study transient sources (see Wallace, Woosley, & Weaver 1982). In particular, only the outer envelope layers of the neutron star characterized by densities less than 10^{10} g cm^{-3} were included in the calculation. Gravity is treated in the Newtonian approximation. The detailed input physics required for the study of the X-ray burst phenomenon is described in Woosley & Weaver (1984). Of primary importance in the present study is the inclusion of the energy generation and compositional variations associated with the rapid proton (rp) capture process (Wallace & Woosley 1981) and electron captures in the reaction $H(e^-, \nu)n(p, \gamma)D$. The former process can be important during the phases corresponding to the peak temperature of the thermonuclear instability, and the latter process can be important for those phases of the evolution where the CNO cycle is inoperative either due to low CNO abundances or low temperatures. The detailed treatment of the nuclear reaction network is especially important for it is essential in the determination of the residual hydrogen abundance remaining after the X-ray burst event. For the numerical results which follow we adopt a neutron star mass and radius of 1.4 $M_\odot$ and 9.1 km, respectively. Based upon the obervations of Aql X-1 we choose a mass accretion rate of 10^{-9} $M_\odot$ yr^{-1} and 2×10^{-12} $M_\odot$ yr^{-1} for the active and inactive burst states, respectively. Furthermore, in order to explore the sensitivity of our results to the initial thermal state of the neutron star, we assume that the initial temperature, T_b, at the base of the accreted layer of the neutron star is either 10^7 K or 1.5×10^7 K. In addition, we assume that the abundance of the accreted matter corresponds to the composition of the intermediate disk population ($X = 0.7$, $Y = 0.299$, $Z = 0.001$).

For the first evolutionary sequence, we consider a neutron star characterized by $T_b = 10^7$ K. Within 15.7 days from the onset of accretion a combined hydrogen-helium flash instability developed in a layer of $\sim 9 \times 10^{22}$ g. A compressional heating phase led to the ignition of hydrogen via the reaction $H(e^-, \nu)n(p, \gamma)D$. As a consequence of the rising envelope temperatures, the nuclear burning evolved to hydrogen burning via the CNO cycle and finally to helium burning as described in earlier works summarized in Joss & Rappaport (1984) and Taam (1985). The resulting light curve of the first X-ray burst is illustrated in Figures 1*a* and 1*b*, and its properties are summarized in Table 1. The burst is characterized by an initial rise time of 7 s to a luminosity of 3×10^{37} ergs s^{-1} followed by a more gradual increase to a peak burst luminosity of 7×10^{37} ergs s^{-1} in an additional 74 s (see Fig. 1*a*). The initial rise is associated with the diffusion of energy released by the rapid burning of helium, and the final rise reflects the longer burning time scales of hydrogen burning via the rp-process.

A prolonged phase ($\sim$6000 s) of X-ray emission is evident during the decay of the burst (see Fig. 1*b*). Specifically, after 2500 s and 6000 s the emission from the neutron star surface corresponds to 12% and 3% of the peak burst luminosity,

TABLE 1

PARAMETERS OF X-RAY BURSTS FOR $T_b = 10^7$ K

Burst	L_{peak} (10^{38} ergs s^{-1})	γ[a]	τ_{rise} (s)[b]	τ_{decay} (s)[c]	τ_{acc} (10^5 s)[d]	ρ (10^6 g cm^{-3})
1.........	0.69	0.14	81	6448	13.56	10.0
2.........	0.34	0.29	31	242	0.23	0.5
3.........	0.22	0.45	12	167	0.10	0.5

[a] Ratio of the persistent emission to the peak burst luminosity, L_{peak}.
[b] Time for the luminosity to increase from 10^{37} ergs s^{-1} to the peak.
[c] Time interval between the peak of the X-ray burst and a luminosity of 2.5×10^{36} ergs s^{-1}.
[d] Time interval required to accrete a critical mass to initiate the thermonuclear instability.

respectively. In contrast to the main peak which is powered by a combination of hydrogen and helium burning reactions, this extended emission is attributable to the energy produced by hydrogen burning alone. We note that the most abundant elements, by mass fraction, at the peak are hydrogen ($X_1 = 0.68$) and Ni ($X_{56} = 0.14$). Since the densities and temperatures at the base of the accreted layer during this phase exceed 5×10^6 g cm^{-3} and 10^9 K, respectively, the first step in the proton burning chain is accelerated by the electron capture process via the reaction H(e^-, ν)n(p, γ)D. The effectiveness of electron captures is made apparent in Figure 2 where the electron capture time scale onto protons is displayed as a function of density and temperature. It is clear that the electron captures will be important in accelerating hydrogen burning in the late phases of the burst when the abundance of CNO seed nuclei is low ($\lesssim 10^{-3}$). At densities $\sim 10^7$ g cm^{-3} and temperatures of 10^9 K the electron capture time scale onto protons is of the order of 3×10^4 s, yielding a nuclear luminosity which is comparable to the preburst persistent level of emission of $\sim 10^{37}$ ergs s^{-1}. Within the decay portion of the burst, the hydrogen abundance is found to decline from 0.68 to 0.59. The contribution of nuclear burning to the total luminosity in the tail amounts to $\sim 70\%$, with the remainder derived from the thermal energy stored in the accreted envelope.

The evolution of the neutron star envelope was followed through two additional X-ray burst events. The thermonuclear runaways in these subsequent events occurred above the base of the first accreted layer. That is, the nuclear shell flash developed in a layer overlying the hydrogen left over after the first flash. The light curves of these two bursts are illustrated in Figure 3. In comparison with the first burst (see Table 1) it is seen that the time scale to accrete a critical amount of mass is significantly decreased to 6.39 hr for the second burst and 2.78 hr for the third burst. The light curve of the second burst is characterized by a rise time of 31 s, a peak luminosity of 3.4×10^{37} ergs s^{-1}, and a decay phase that is distinguished by the absence of a long X-ray tail. This is a consequence of the higher envelope temperature and therefore lower density at which hydrogen ignition occurs. As a result, a much smaller amount of mass accumulates ($\sim 1.5 \times 10^{21}$ g). In both of these

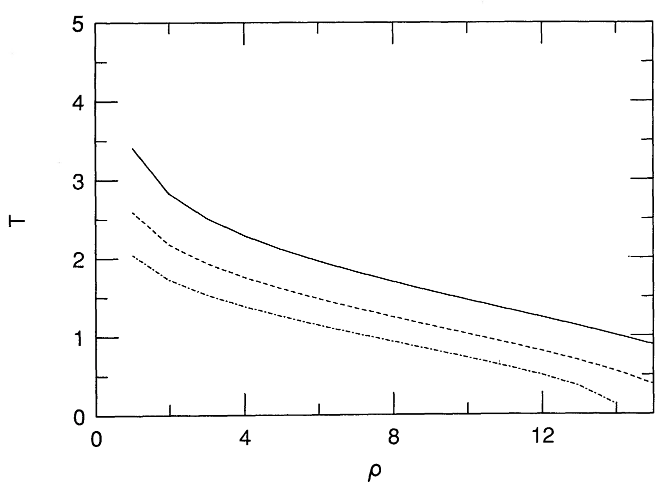

FIG. 2.—The relation between the density, ρ, and the temperature, T, for a given electron capture time scale at $Y_e = 0.845$ where Y_e is the reciprocal of the mean molecular weight of the electrons. The density is in units of 10^6 g cm^{-3} and the temperature is in units of 10^9 K. The solid, dashed, and dashed dotted curves correspond to time scales of 10^4, $10^{4.5}$, and 10^5 s respectively.

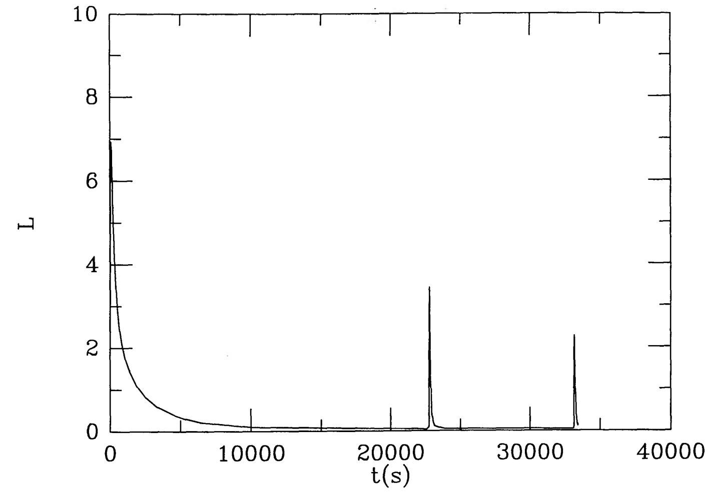

FIG. 3.—The luminosity profile for the second and third X-ray bursts produced in the case characterized by a temperature at the base of the accreted layer of 10^7 K. The luminosity, L, is in units of 10^{37} ergs s^{-1}. The origin of time has been shifted to the occurrence of the first X-ray burst. Note the relatively short accumulation time scale required to initiate the thermal instability as compared to the first burst (see Table 1).

subsequent bursts there is some evidence for residual emission lasting several hundred seconds after the burst peak. In particular, at 350 s after burst maximum the X-ray flux is still 10% above the preburst level. Because of the diversity in the properties of the X-ray bursts the results clearly demonstrate the effects of thermal inertia in the neutron star envelope (Taam 1981). Comparing the properties of the third X-ray burst with the second, it appears that the bursting behavior is evolving toward a limit cycle (where the differences in burst properties are reduced from burst to burst) for the assumed mass accretion rate independent of the assumed initial thermal state of the neutron star (see also Hanawa & Fujimoto 1984). The envelope structure, however, has not reached a steady state, as evidenced by the fact that the compositional profile continually evolves in time.

To determine the sensitivity of our results for the first X-ray burst to the thermal state of the neutron star, we used the global analysis of Fushiki & Lamb (1987) as a guide and increased T_b from 10^7 K to 1.5×10^7 K. The properties of the X-ray bursts are summarized in Table 2 and the luminosity profile of the first burst is displayed in Figure 4. We note that the decay phase of the first X-ray burst is significantly shorter than that corresponding to the low-temperature case (compare to Fig. 1*a*). For example, the luminosity from the stellar surface at 1300 s after the onset of the burst is 1.5×10^{36} ergs s^{-1} or about 10 times lower than for the low-temperature case. Nearly the entire luminosity emitted during the decay reflects the thermal energy radiated from within the accreted envelope. The shorter decay phase is attributable to the fact that the critical accumulated mass required to initiate the thermal instability in the accreted layer is smaller for higher envelope temperatures. As a result of this dependence on the envelope temperature, the critical accumulated mass (and corresponding density) required to initiate the thermonuclear runaway amounted to only 3×10^{22} g. In this case, the electron capture processes are unimportant. As a consequence, the contribution of nuclear burning to the luminosity during the decay phase amounted to less than 10%. Thus, the duration of the X-ray tail proves to be an excellent diagnostic for the thermal state of

TABLE 2

PARAMETERS OF X-RAY BURSTS FOR $T_b = 1.5 \times 10^7$ K

Burst	L_{peak} (10^{38} ergs s^{-1})	γ[a]	τ_{rise} (s)[b]	τ_{decay} (s)[c]	τ_{acc} (10^5 s)[d]	ρ (10^6 g cm^{-3})
1.........	0.84	0.12	13	1291	5.02	5.0
2.........	3.10	0.03	9	866	1.64	0.5

[a] Ratio of the persistent emission to the peak burst luminosity, L_{peak}.
[b] Time for the luminosity to increase from 10^{37} ergs s^{-1} to the peak.
[c] Time interval between the peak of the X-ray burst and a luminosity of 2.5×10^{36} ergs s^{-1}.
[d] Time interval required to accrete a critical mass to initiate the thermonuclear instability.

the neutron star. The properties of the subsequent bursts for both the low- and high-temperature cases are similar to each other, thus providing further support for the result that their properties are not sensitive to the initial thermal state of the neutron star.

In order to determine the consistency of the initial thermal state of the neutron star core prior to the recurrent transient outburst with its cooling behavior between major outbursts, we have also studied the thermal evolution of the envelope during the quiescent state. Specifically, the accretion rate onto the neutron star was decreased suddenly to 2×10^{-12} $M_\odot$ yr^{-1}, and the evolution of the neutron star envelope was followed for 1 yr. It was found that the temperature of the envelope relaxed to its initial thermal state and tended to an isothermal structure after a period of 1 month subsequent to the cessation of the bursting activity. Hence, the history of the thermal evolution occurring during the transient outburst event is lost (Hanawa & Fujimoto 1986). During this time the temporal variation of the temperature at the base of the accreted layer is described by the relation $T_b \propto t^{0.47}$. Because of the rapid decline to the initial thermal state between major transient outbursts, the assumed initial thermal state for the neutron star is consistent with its cooling behavior.

The actual accretion rate onto the neutron star during the major outburst is time dependent. We, therefore, have also examined the dependence of the critical accumulated mass, ΔM, required to initiate the thermonuclear instability to the time-averaged rate of mass accretion for $T_b = 10^7$ K. For accretion rates greater than 10^{-9} $M_\odot$ yr^{-1}, it is found from

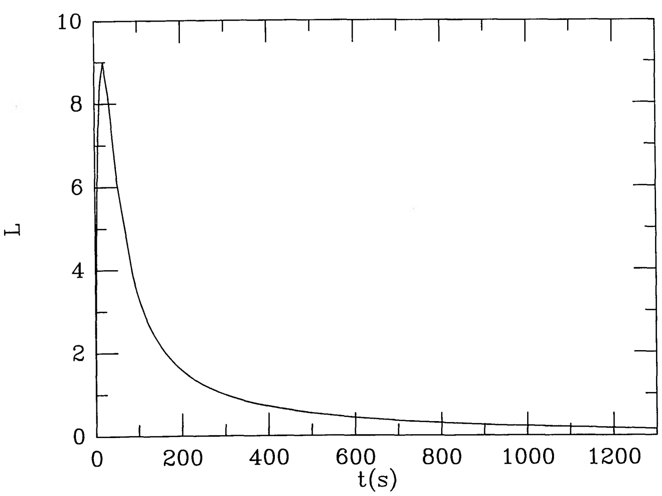

FIG. 4.—The luminosity profile of the first X-ray burst produced after the onset of accretion for the case corresponding to $T_b = 1.5 \times 10^7$ K. The luminosity, L, is in units of 10^{37} ergs s^{-1}. Note that the X-ray tail is significantly shorter than that corresponding to $T_b = 10^7$ K (see Fig. 1*a*).

numerical calculations that

$$\Delta M = 9 \times 10^{22} \left(\frac{\dot{M}}{10^{-9}\ M_\odot\ \mathrm{yr}^{-1}} \right)^{-0.33} \mathrm{g}\,, \tag{1}$$

where $\dot{M}$ is the mass accretion rate. For accretion rates less than 10^{-9} $M_\odot$ yr^{-1} the critical accumulated mass is insensitive to the accretion rate since the electron capture time scale is sufficiently short to initiate the runaway independent of the mass accretion rate. From equation (1) it is seen that the critical accumulated mass decreases slightly with increasing accretion rate. This suggests that the results found for the long X-ray tail are not very sensitive to the mass accretion rate. The dependence exhibited in equation (1) can be understood in terms of the effects of compressional heating in the accreted envelope. As the mass accretion rate is increased, the degree to which the temperatures within the accreted layer increase are greater and, hence, less matter is required to initiate the thermal instability. The evolution to ignition of the nuclear fuel is determined by compressional heating in this range of mass accretion rates and does not depend on the thermal state of the neutron star provided that the initial envelope temperatures are $\lesssim 10^7$ K (see also Hanawa & Fujimoto 1984; Fushiki & Lamb 1987). Similarly, the results are also insensitive to the metal abundance of the accreted matter since the nuclear fuel is ignited at low temperatures.

3. DISCUSSION

We have modeled the extended phase of X-ray emission discovered by Czerny et al. (1987) in the X-ray burst seen from the recurrent transient Aql X-1 in terms of a prolonged phase of hydrogen burning accelerated by electron captures following the first X-ray burst emitted during the transient outburst. This interpretation is in contrast to the work of Czerny et al. (1987), who proposed an interpretation in terms of enhanced mass flow from the accretion disk. In this latter model, if one assumes that the radiation of the neutron star is responsible for the increased rate of mass accretion, it is unclear why it should last so much longer than the duration of a typical X-ray burst event (~ 20 s) and why the extended tails should not be seen after all bursts. The former concern follows from the fact that the influence of radiation on the mass flow within the disk is primarily localized in the region where the local viscous time scale is comparable to the duration of the burst. For the regions of the disk where the viscous time scale is longer than the burst event, the column density would not change significantly. Although the temperature and, hence, the viscosity would change on the local thermal time scale of the disk, the effect of external radiation is significantly decreased after the burst and the temperatures in the disk will be determined by the local balance of energy generation due to viscous heating and cooling by radiative transport. One would conclude that the influence of external heating on increasing the local mass transport rate within the disk is important only when the radiation emitted from the surface of the neutron star overwhelms that emitted by the disk. Interpretations of the prolonged X-ray tail in terms of enhanced mass flow from the companion star induced by the X-ray burst radiation also are untenable since the expected emission is not expected to be produced immediately after the X-ray burst event. On the contrary, the time scale for matter to flow to the inner X-ray emitting regions of the disk is much too long (comparable to the decay time scale of the soft X-ray transient which is of the order of weeks).

In contrast, a prolonged phase of hydrogen burning accelerated by electron captures can successfully explain the long X-ray tails observed in Aql X-1. Within this model, the observations provide an important diagnostic probe of the physical conditions in the nuclear burning regions. In particular, they provide a stringent constraint on the mass accreted by the neutron star and its envelope temperatures prior to the first X-ray burst event (see also Hanawa & Fujimoto 1986). This follows from the fact that electron capture rates onto protons are very sensitive to the density at the base of the accreted layer. An estimate of the accreted mass can be derived from the density at which the electron capture time scale decreases rapidly. For densities of 10^7 g cm^{-3}, where the time scale can be as fast as 10^4 s, the accumulated mass amounts to $\sim 9 \times 10^{22}$ g for a neutron star of 1.4 $M_\odot$ and a radius of 9.1 km. As seen from the results of the previous section the envelope temperatures must be less than 1.5×10^7 K in order that such a large mass be accumulated prior to the onset of a thermonuclear runaway.

Although the rise time scale of the first X-ray burst calculated for the low-temperature case is longer than that observed from Aql X-1, the time scale can be reduced by a slightly higher envelope base temperature (which would also reduce the duration of the X-ray tail; compare the two cases in the previous section). In addition, the inclusion of electron captures onto nuclei participating in the nuclear flow in the rp-process would also lead to a shorter rise time for the burst.

The time-averaged accretion rate can be estimated directly from equation (1) using the result that the first observed X-ray burst was seen at least 9 days after the peak of the accretion-driven transient outburst. We find that the time-averaged mass accretion rate $\dot{M} \lesssim 1.6 \times 10^{-9}$ $M_\odot$ yr^{-1}. This result, coupled with the fact that the peak luminosity of the X-ray burst (typically comparable to the Eddington limit) is about 10 times larger than the peak luminosity of the transient outburst, provides additional support for our requirement that the mass of the accumulated layer in the envelope is large ($\sim 10^{23}$ g) and the envelope temperatures are low ($\lesssim 1.5 \times 10^7$ K).

General relativistic effects, which have been neglected in the present investigation, can lead to modification of the above estimates (see Ayasli & Joss 1982) since the gravitational redshift factor for the assumed mass and radius of the neutron star is 1.36. Because of these effects the luminosities emitted by the neutron star should be reduced by a factor of 1.85 and the time scales increased by a factor of 1.36. Although other general relativistic corrections can lead to more complex corrections due to the equations of stellar structure (Thorne 1977), it is expected that differential comparisons between models presented in the previous section will not be changed significantly for numerical models in which these corrections are included.

Our model requires that the long X-ray tail is associated only with the first X-ray burst emitted by the recurrent transient. Our calculations show that thermal inertia effects are very important in determining burst systematics, since the time scale to accrete sufficient mass to initiate the subsequent thermonuclear runaways can be much shorter (by a factor of 60–140 for Aql X-1) than in the case of the first burst. As a result the subsequent bursts are correspondingly less energetic. As applied to Aql X-1 the subsequent bursts exhibit recurrence time scales of $\sim$3–7 hr and shorter X-ray tails during the decay phase.

Future studies of X-ray bursts from transient sources offer the promise for understanding the qualitatively different behaviors exhibited by neutron stars out of thermal equilibrium. Such studies may be especially relevant to the erratic correlations between accretion rate and burst behavior exhibited by such sources as 0748−67 (Gottwald et al. 1986) and 1608−52 (Murakami et al. 1980).

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REFERENCES

Ayasli, S., & Joss, P. C. 1982, ApJ, 256, 637
Belian, R. D., Conner, J. P., & Evans, W. D. 1972, ApJ, 171, L87
Czerny, M., Czerny, B., & Grindlay, J. E. 1987, ApJ, 312, 122
Fujimoto, M. Y., Hanawa, T., & Miyaji, S. 1981, ApJ, 246, 267
Fushiki, I., & Lamb, D. Q. 1987, ApJ, 323, L55
Gottwald, M., Haberl, F., Parmar, A., & White, N. E. 1986, ApJ, 308, 213
Hanawa, T., & Fujimoto, M. Y. 1982, PASJ, 34, 495
———. 1984, PASJ, 36, 199
———. 1986, PASJ, 38, 13
Joss, P. C., & Rappaport, S. 1984, ARA&A, 22, 537
Kaluzienski, L., J., Holt, S. S., Boldt, E. A., & Serlemitsos, P. J. 1977, Nature, 265, 606
Koyama, K., et al. 1981, ApJ, 247, L27
Murakami, T., et al. 1980, ApJ, 240, L143
Taam, R. E. 1981, ApJ, 247, 257
———. 1985, Ann. Rev. Nuc. Part. Sci., 35, 1
Thorne, K. S. 1977, ApJ, 212, 825
Wallace, R. K., & Woosley, S. E. 1981, ApJS, 43, 389
Wallace, R. K., Woosley, S. E., & Weaver, T. A. 1982, ApJ, 258, 696
Woosley, S. E., & Weaver, T. A. 1984, in High Energy Transients in Astrophysics, ed. S. E. Woosley (AIP Conf. Proc. 115), 273