TITLE: A 1-D THERMONUCLEAR MODEL FOR X-RAY TRANSIENTS

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SUBMITTED TO: Proceedings of the Accreting Neutron Star Conference
Garching, W. Germany

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Submitted to: Proceedings of the Accreting Neutron Star Conference, Garching, W. Germany, July 1982.

I. INTRODUCTION

The thermonuclear evolution of a 1.41 $M_\odot$ neutron star, with a radius of 14.3 km, accreting various mixtures of hydrogen, helium, and heavy elements at rates of 10^{-11} to 10^{-10} $M_\odot$/yr is examined, in conjunction with S. E. Woosley and T. A. Weaver, using a one-dimensional numerical model. We have ignored any effects due to general relativity or magnetic fields. Two cases shall be discussed. In both models, the accretion rate is such that the hydrogen shell burns to helium in steady state, with the hydrogen burning stabilized by the β-limited CNO cycle. A thick helium shell is produced, which is eventually ignited under extremely degenerate conditions, producing a thermonuclear runaway.

II. MODEL A

Material with a composition of X=0.70, Y=0.2991, and $Z=9\times10^{-4}$ was accreted at a rate of 1×10^{-10} $M_\odot$/yr. The metal deficient composition may result either from placement of the neutron star in a binary system with a Population II red giant or from gravitational settling of heavy ions in the accreted material. Nearly identical helium envelope conditions can also be obtained by accreting solar metallicity material at 3.5×10^{-10} $M_\odot$/yr. Such parameters should lead to an outburst essentially identical to Model A. A stable hydrogen layer containing 6×10^{21} gm was obtained in Model A, with a base temperature and density of 1.2×10^{8} K and 4×10^{5} g cm^{-3} respectively. When the helium layer reached a mass of 1.4×10^{23} g (corresponding to an accretion timescale of 7 months), and a base density of 6×10^{6} g cm^{-3}, a helium runaway occurred. Temperatures at the base of the burning region reached 3.2×10^{9} K, with plasma velocities of 10^{7} cm/s. The nuclear fuel was completely consumed by a deflagration wave, burning the entire envelope to ^{56}Ni and releasing 1.28×10^{41} erg of photon energy.

The light curve for this event is shown in Figure 1. Super-Eddington luminosities in the envelope drives material off the surface of the star at a rate of about 10^{18} g/s. The photosphere is driven out to a radius of about 30 km, where it then emits soft x-rays ($T_{eff} \approx 10^{7}$ K) at the Eddington luminosity ($L_{ed} \approx 2\times10^{38}$ erg/s). The mass-loss phase lasts about 300s, during which the photosphere decreases to the initial neutron star radius. Since $L \approx L_{Ed} \approx$ constant, the photospheric motion causes a rise in T_{eff} to a maximum, and then a decline as the luminosity drops below the Eddington value.

III. ODEL B

Material with a composition X=0.70, Y=0.29996, and $Z=4\times10^{-5}$ was accreted at a rate of 2×10^{-11} /yr. Again, the ensuing outburst could also be obtained for higher metallicities by using a different accretion rate. The stable 2.4×10^{22} g hydrogen layer was characterized by $T_H=7.45\times10^{-7}$ K and $\rho_H=1.14\times10^{6}$ g cm^{-3} at its base. The lower temperature for Model B allowed it to accumulate a thicker, more degenerate, helium layer (1.0×10^{25}g) than Model A. When the base of the helium shell reached a density of 1.1×10^{8} g cm^{-3}, a violent helium runaway occurred. A peak temperature of 6×10^{9} K was reached in the helium layer, and the burning front steepened into a shock wave as it moved toward the surface. The detonation wave burned all fuel to ^{56}Ni and released 1.5×10^{43} erg, mostly in neutrinos (1.9×10^{42} erg in photons). Very brief ($\approx$30 ns) gamma emission at $\approx10^{42}$ erg/s occur as the shock breaks through the neutron star surface. Within 0.1 ms, the superheated envelope expands to about 30 km, and the luminosity remains roughly constant at the Eddington value for 2 hours.

The light curve for this event is shown in Figure 2. The effective temperature again evolves from soft to hard to soft due to the photospheric motion. The 1 ms rise time of the main event is much faster than the diffusion time through the envelope. However, this number is somewhat misleading because the observable risetime would be dominated by the propagation time around the star from a presumably point initial detonation.

IV. CONCLUSIONS

The values of accretion rate and metallicity considered here produce x-ray transients lasting minutes to hours. Such rapid transients as ANS0208-7 and GX355+3 might be explained by such a mechanism; however, we do not produce the x-ray precursors observed in some of these events. Lower accretion rates and metallicities produce more violent events of greater duration. Radiatively driven mass loss can occur from the super-heated neutron star surface. Dynamic photospheric behavior results in a soft-hard-soft spectral evolution. Two qualitatively different burning mechanisms can be produced: convective deflagration or detonation. Further details of these calculations are contaied in Wallace, Woosley, and Weaver (1982). Extension of these models to the 2D gamma burst case is found in Woosley and Wallace (1982).

Several inadequacies of the present models and suggestions for future research should be mentioned. The Lagrangian nature of our code prevents a detailed study of the dynamic photosphere behavior. An implicit Eulerian code or analytic work should be used to more accurately determine the light curve and effective temperature evolution during the outburst. The complete neutron star, with accurate cooling physics, should be included to determine its thermal effect on the burning envelope. Gravitational diffusion of high-Z elements should be explicitly included in the accretion evolution calculations (thus requiring a diffusion coefficient that is valid in degenerate media). Both general (due to the strong neutron star gravitational potential) and special (to calculate the mass outflow velocities) relativistic corrections to the hydrodynamic equations should be considered. Lower accretion rates and cooler neutron stars should be invesigated. These latter regimes will require inclusion of electron-capture and pycnonuclear reactions, as well as much improved electron screening corrections for the liquid phase. Finally, accurate radiation transport in the outer envelope will be required to determine the true spectral distribution for the burst emission. The x-ray precursors to the rapid x-ray transients (Hoffmann, et. al. 1978) remain unexplained phenomenon.

V. REFERENCES

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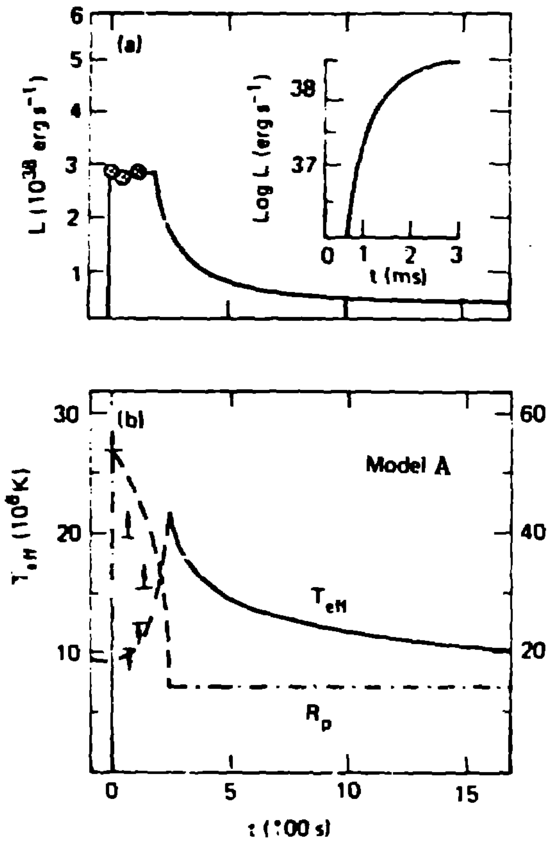

Figure 1.

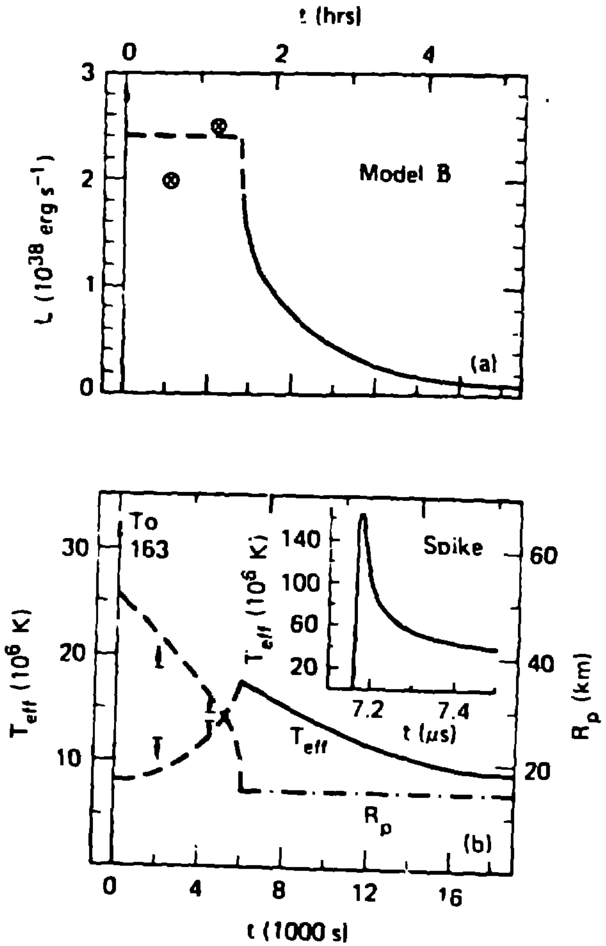

Figure 2.