THERMONUCLEAR PROCESSES ON ACCRETING NEUTRON STARS

Paul C. Joss
Department of Physics
and
Center for Theoretical Physics
Massachusetts Institute of Technology

I. INTRODUCTION

The observed properties of X-ray burst sources have recently been reviewed by Lewin and Clark (1980) and Lewin and Joss (1980). About thirty-five such sources are presently known, and they have a spatial distribution reminiscent of stellar Population II (see Figure 1). The salient features of these sources include burst rise times of $\lesssim 1$s, decay time scales of ~ 3-100 s, peak luminosities of $\sim 10^{39}$ ergs per burst, spectra that can generally be well fitted by blackbody emission from a surface with a constant effective radius of ~ 10 km and a peak temperature of $\sim 3 \times 10^7$ K, and "tails" of softer X-ray emission that may persist for several minutes after the burst maximum. Profiles of bursts from some typical burst sources are shown in Figure 2. The intervals between bursts from a given source may be regular or erratic and are typically in the range of $\sim 10^4$-10^5 s; many sources undergo burst-inactive phases that can last for weeks or months. Most burst sources are also sources of persistent X-ray emission, and the ratio of average persistent luminosity to time-averaged burst luminosity is typically $\sim 10^2$ during burst-active phases. (The properties of the "Rapid Burster," MXB1730-335, are different from those of all other known burst sources and will be discussed separately in §VI below.) There are few correlations among the burst flux, burst intervals, and persistent X-ray flux from any given source, and the detailed burst shapes vary from one source to another and often vary with time in a given source.

A theoretical model for X-ray burst sources ideally should account for all these observational properties. Nearly all models that have been proposed so far assume that the bursting phenomenon involves accretion of matter onto a collapsed object (degenerate dwarf, neutron star, or black hole). In all cases, the collapsed object serves at least one of two functions: its deep gravitational potential well allows the release of large amounts of gravitational energy in the form of X-radiation by the accreting matter, and its small dimensions permit the X-ray emission to be released on the short time scale of an X-ray burst.

D. Sugimoto, D. Q. Lamb, and D. N. Schramm (eds.), Fundamental Problems in the Theory of Stellar Evolution, 207–227.

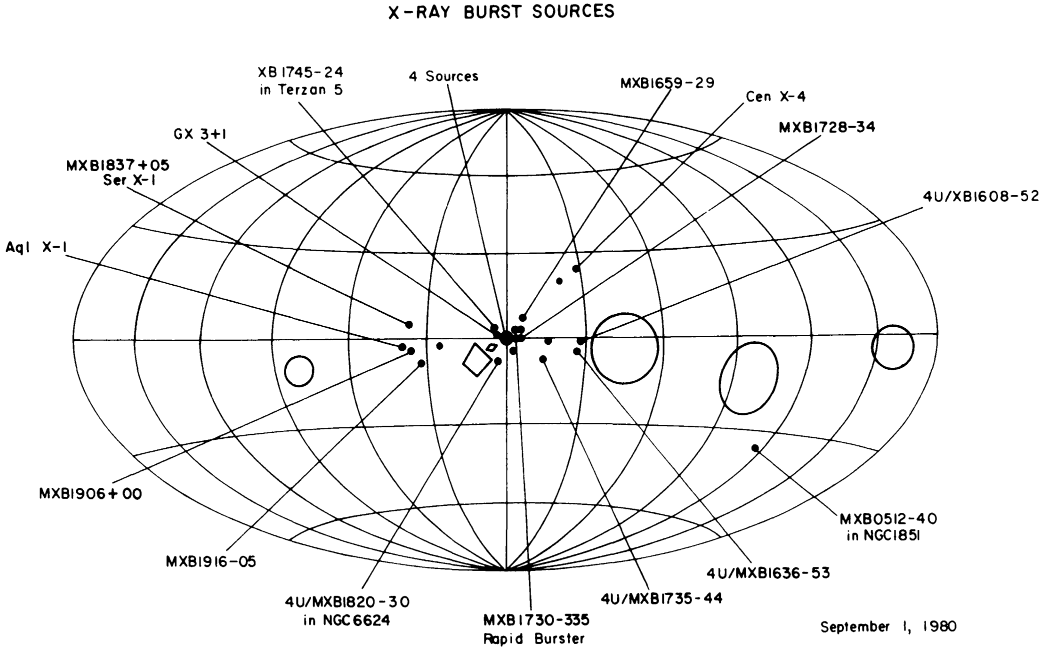

Figure 1. Map of 31 X-ray burst sources with accurately known positions as of September 1, 1980, in galactic coordinates (from Lewin and Joss 1980). The concentration of these sources in the direction of the galactic center, together with the association of several of them with globular clusters, strongly suggests an identification with an old stellar population (see Lewin and Joss 1980).

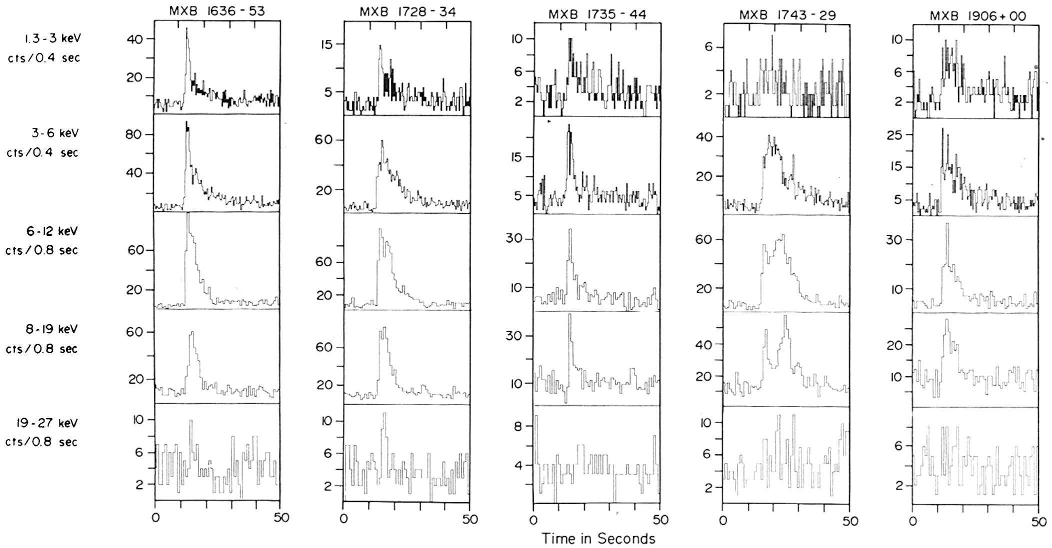

Figure 2. Profiles, in five energy channels, of X-ray bursts from five different burst sources (from Lewin and Joss 1977).

The proposed models can be broken down into two broad classes: (1) those invoking instabilities in the accretion flow onto a collapsed object, and (2) those that invoke thermonuclear flashes in the surface layers of an accreting neutron star. Models in class (1) were reviewed by Lamb and Lamb (1977). Although a few new models in this class have been proposed in the past several years, relatively little progress has been achieved in understanding the complex hydrodynamics and radiative transfer that all such models entail (see, however, Cowie, Ostriker, and Stark [1979] for a discussion of physical constraints on many of these models). During the past few years, the greatest amount of progress has instead been achieved in developing the thermonuclear flash model, which has proved to be amenable to detailed numerical computations. As will be documented below, these calculations have been remarkably successful in accounting for the general properties of the bursts from most X-ray burst sources. Moreover, the theoretical work to date strongly suggests that the characteristics of X-ray bursts should be capable of imparting substantial constraints upon the properties (masses, radii, internal temperatures, and so forth) of the underlying neutron stars.

II. HISTORICAL DEVELOPMENT

When X-ray pulsars were discovered in 1971 (Giacconi et al. 1971; Lewin, McClintock, and Ricker 1971; Schreier et al. 1972; Tananbaum et al. 1972), it was immediately recognized that these objects were probably neutron stars that were undergoing accretion from binary stellar companions. Soon thereafter, in 1973, Rosenbluth et al. (1973) pointed out that nuclear fusion in the surface layers would be an independent source of energy that might be radiated from the neutron-star photosphere. A few years later, in 1975, Hansen and Van Horn (1975) demonstrated that over a wide variety of conditions, the nuclear burning ought to be unstable and should lead to thermonuclear flashes.

Hansen and Van Horn (1975) noted that the energy released in such flashes might produce variable X-ray emission from the neutron star. However, they also discovered that the characteristic time scale for thermonuclear runaway was usually $\lesssim 1$ s. This was considerably shorter than most of the time scales of variability from X-ray sources that were then known (with the exception of the periodic pulses from X-ray pulsars). Van Horn and Hansen (1974) attempted to construct a hydrogen-flash model for the transient X-ray sources (which typically have rise times of a few days and decay time scales to weeks to months), but they were forced to resort to extremely low-mass ($\lesssim 0.15\ M_{\odot}$) neutron stars to get sufficiently thick hydrogen-rich envelopes and sufficiently long runaway time scales.

Following the discovery of X-ray bursts by Grindlay et al. (1976) in September 1975, a number of possible explanations for this phenomenon were soon advanced. Among the early proposals was the suggestion by Woosley and Taam (1976) and

Maraschi and Cavaliere (1977) that X-ray bursts result from thermonuclear flashes on accreting neutron stars. This suggestion spurred more detailed investigations by Joss (1977), Lamb and Lamb (1978), and Taam and Picklum (1978) into the physics of nuclear flashes on accreting neutron stars and their possible relation to X-ray bursts. Subsequently a number of authors, including Joss (1978), Taam and Picklum (1979), Joss and Li (1980), Fujimoto, Hanawa, and Miyaji (1980), and Taam (1980) have presented the results of detailed numerical computations of flashes of this type. Other discussions of various aspects of thermonuclear flashes on accreting neutron stars have been presented by Czerny and Jaroszyński (1979), Ergma and Tutukov (1980), Hoshi (1980), and Barranco, Buchler, and Livio (1980).

III. THE OVERALL PHYSICAL PICTURE

Consider a neutron star undergoing accretion from a binary stellar companion. The freshly accreted matter will be rich in hydrogen and/or helium. However, at depths $\gtrsim 10^4$ cm beneath the surface of the neutron star, the density is sufficiently high that nuclear statistical equilibrium will be swiftly achieved; the predominant nuclei will have maximal binding energies, with atomic weights of ~60. (Still deeper in the star, these nuclei dissolve into a fluid in which neutrons are the primary constituent.) Hence, the accreting matter must pass through a series of nuclear burning shells as it is gradually compressed by the accretion of still more material. If the core of the neutron star is sufficiently hot or the accretion rate is sufficiently high, the temperature in the surface layers will be high enough that the burning will proceed via thermonuclear reactions, rather than electron capture or pycnonuclear reactions (which are driven by high densities rather than high temperatures). A sketch of the resultant structure of the neutron-star surface layers is given in Figure 3.

It was first realized by Hansen and Van Horn (1975) that these burning shells will tend to be unstable to thermal runaway. The instability, known as the "thin-shell instability", was first discovered in a different context by Schwarzschild and Härm (1965). The existence and strength of the instability are a direct result of the strong temperature dependence of the thermonuclear reaction rates. In the case of neutron-star envelopes, the instability is further enhanced by the partial degeneracy of the burning material. A cogent and thorough technical discussion of this type of instability has been given by Giannone and Wiegert (1967) (see also Barranco, Buchler, and Livio 1980).

The p-p chains are insufficiently temperature-sensitive to produce a thermal runaway in the hydrogen-burning shell of a neutron star. The instability of this shell is thus largely quenched by the saturation of the CNO cycle at very high reaction rates (Joss 1977; Lamb and Lamb 1978). The saturation results from the appreciable lifetimes (~10^{2-3} s) of the beta-unstable nuclei N^{13}, O^{14}, O^{15} and F^{17} that participate in the cycle. For low neutron-star core temperatures ($\lesssim 1 \times 10^8$ K) the shell can

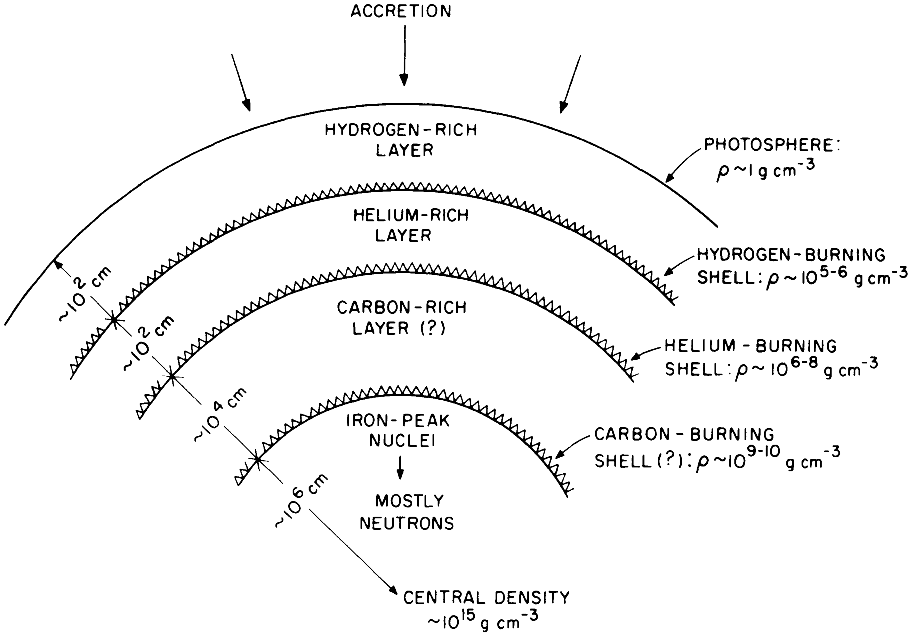

Figure 3. Schematic sketch of the surface layers of an accreting neutron star (from Joss 1979a).

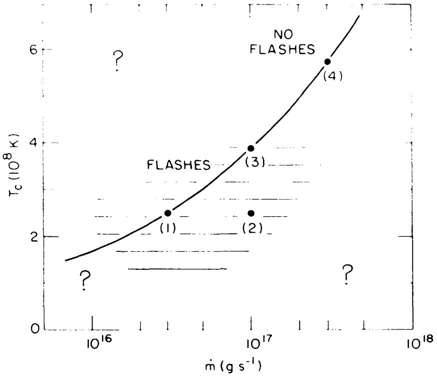

Figure 4. Mass accretion rates ($\dot{m}$) and core temperatures (T_c) for the evolutionary models of the helium-burning shell by Joss (1978). Points 1 through 4 denote the parameter values used in four models. All models assume a neutron-star mass of 1.4 $M_\odot$, a radius of 6.6 km, no magnetic field, and spherical symmetry. The solid curve passing through points 1, 3, and 4 is the estimated locus of parameter values for which the core of the neutron star is in thermal equilibrium (see text). Models 1, 2, and 3 all displayed thermonuclear flashes in the helium-burning shell; the hatched region denotes the range of parameter values for which flashes may be expected. The helium-burning shell in model 4 did not display flashes; the shell evidently becomes thermally stable at high values of T_c and $\dot{m}$, for reasons explained by Joss (1978). The behavior of the helium-burning shell at low values of T_c and $\dot{m}$ remains unexplored, but it is anticipated that flashing behavior will disappear at very low values of T_c and $\dot{m}$ ($T_c < 10^8$ K and $\dot{m} < 10^{15}$ g s^{-1}; Lamb and Lamb 1978). Also unexplored is the behavior of the helium-burning shell for parameter values far from the equilibrium curve (the upper left-hand and lower right-hand corners of the figure). (From Joss 1979a.)

in principle be unstable, but any runaways will be halted by the saturation effect before the release of a substantial amount of energy (see, however, the discussion of interacting hydrogen-helium shells in §IV below). The next shell inward is the helium-burning shell, which should be unstable over a wide range of conditions. It is uncertain whether there will be any other significant burning shells, as the matter might already burn to quite heavy elements in the helium shell (Taam and Picklum 1978; Joss 1978). However, if a carbon shell exists, it is very likely to be unstable also (Woolsey and Taam 1976; Taam and Picklum 1978).

Dimensional analysis (Joss 1977; Lamb and Lamb 1978) indicates that the helium-burning flashes should have the following properties: (1) They should occur after the accumulation of $\lesssim 10^{21}$ g of fuel and release total energies of $\lesssim 10^{39}$ ergs per flash. (2) For accretion rates comparable with those observed in X-ray pulsars ($\lesssim 10^{17}$ g s^{-1}), the time interval between flashes should be $\sim 10^4$ s, very roughly. (3) The transport of energy through the surface layers should result in the emission of bursts of electromagnetic radiation from the neutron-star photosphere with rise times of ~0.1 s, peak luminosities of $\sim 10^{38}$ ergs s^{-1}, decay time scales ~10 s, and peak blackbody temperatures of $\sim 3 \times 10^7$ K (if a full 10^{39} ergs of energy is indeed released in a single flash).

Carbon-burning flashes, if they exist, would occur much deeper beneath the neutron-star surface ($\sim 10^4$ cm, compared to $\sim 10^2$ cm for the helium shell) and would result in the release of substantially more energy. Hence, the duration of a "burst" resulting from a carbon flash should be much longer than for a helium flash (Joss 1977), unless dynamical effects are generated in the outermost surface layers.

IV. NUMERICAL MODELS

The above estimates, though very crude, suggest that thermonuclear flashes on accreting neutron stars could account for the observed properties of X-ray burst sources. With this encouragement, detailed numerical computations of the evolution of the surface layers of an accreting neutron star have been carried out.

Joss (1978) explored the evolution of the helium-burning shell (see also Hoshi 1980). In these calculations, the neutron star was chosen to have a mass of $M = 1.4\ M_\odot$ and a radius of $R = 6.6$ km. A simplified nuclear reaction network was used, incorporating the dominant reactions linking the nuclei from He^4 to Si^{28} and allowing the release of most of the available nuclear energy. The accretion was assumed to be spherical and the star was taken to be nonrotating and unmagnetized, so that spherical symmetry could be assumed throughout the calculations. The effects of hydrogen burning upon the structure of the surface layers was also neglected. The importance of these assumptions and approximations will be discussed below.

Joss' (1978) models contain two free parameters: the mass accretion rate, $\dot{m}$, and the core temperature of the neutron star, T_c. The values of $\dot{m}$ and T_c used in four models are indicated in Figure 4. If the core of the neutron star is in thermal equilibrium (i.e., if the heat flow into the core from the surface layers during thermonuclear flashes is just balanced by the heat lost from the core between flashes), then there is a unique relationship between $\dot{m}$ and T_c (Lamb and Lamb 1978); the estimated locus of these equilibrium values, as given by Joss (1978) (see also Joss and Li 1980), is shown in Figure 4. Three of the four models calculated by Joss (1978) displayed thermonuclear flashes in the helium-burning shell (see Figures 5 through 7). The properties of these flashes were in good agreement with those expected from dimensional analysis (Joss 1977; Lamb and Lamb 1978; see §III). More importantly, these calculations indicated that (1) a full $\sim 10^{21}$ g of matter accumulates on the neutron-star surface before each helium flash, (2) a flash consumes virtually all the available nuclear fuel and probably synthesizes mostly iron-peak elements, and (3) most of the energy of a flash is transported to the photosphere and lost as X-radiation, rather than carried inward to heat the interior of the star. These properties of the flashes had not been discerned prior to the performance of detailed evolutionary computations, at least in part because they depend upon the highly nonlinear characteristics of the flash growth and decay.

The behavior of the helium-burning shell was further explored by Joss and Li (1980), who investigated the sensitivity of the flash properties to the assumed mass and radius of the neutron star. They argued that since each helium-burning flash apparently consumes virtually all the available nuclear fuel, the nuclear physics essentially factors out of the problem and most of the mass- and radius-dependence of the flash properties follow from a few basic physical considerations. Thus, the recurrence interval τ_R between flashes is just the amount of time required for the base of the helium-rich layer to reach the critical temperature and density for a flash to commence, which is roughly proportional to the surface area ($A = 4\pi R^2$) of the neutron star and the scale height in its surface layers. The scale height, in turn, is roughly inversely proportional to the surface gravity $g = GM/R^2$. It then follows that

$$\tau_R \sim A\, g^{-1} \sim R^4\, M^{-1}. \qquad (1)$$

Similarly, the peak surface X-ray luminosity (L_{max}) following a flash just scales as the Eddington limit (Joss 1977), which is proportional to M but is independent of R; thus,

$$L_{max} \sim M. \qquad (2)$$

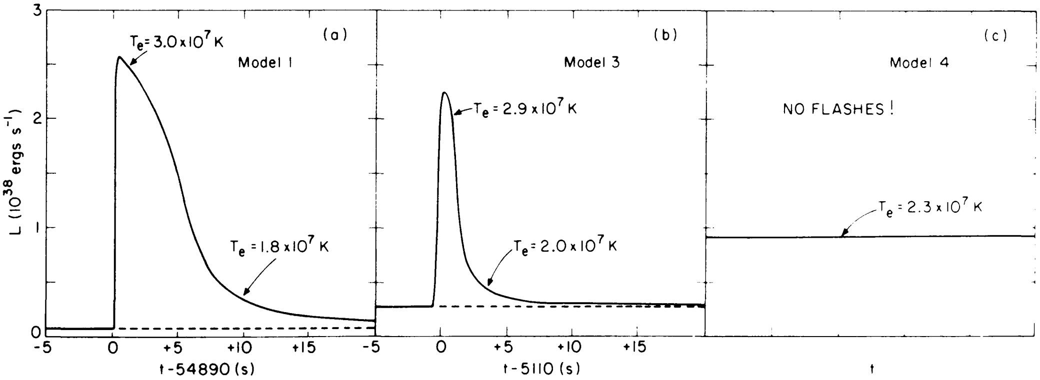

Figure 5. (a) The behavior of the surface luminosity L following a thermonuclear flash in model 1 by Joss (1978) (see Fig. 4). (b) Same for model 3. In each case, time t = 0 is at the start of accretion onto the neutron-star surface, the dashed line denotes the level of persistent accretion-driven luminosity, and the effective blackbody temperature (T_e) is indicated at a few points. The properties of these luminosity variations are in remarkably good agreement with the typical properties of observed X-ray bursts (see text). (c) The surface luminosity behavior for model 4. No flashes occur at the high core temperature and accretion rate of this model, so that the nuclear energy generation rate does not vary greatly and never produces more than a small perturbation on the accretion-driven luminosity. (From Joss 1979a.)

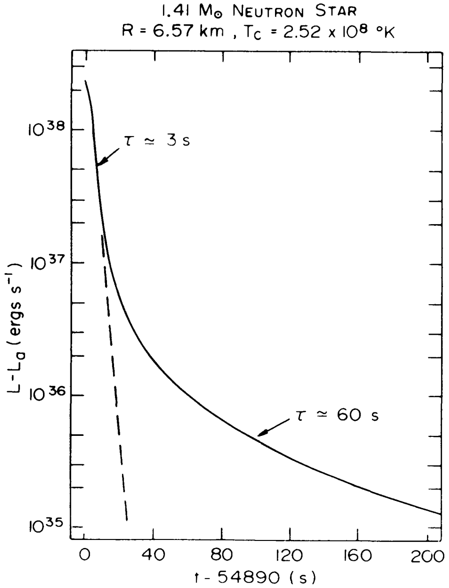

Figure 6. The decline from maximum X-ray luminosity in model 1 by Joss (1978), on time scales longer than those shown in Figure 5. L_a is the level of persistent accretion-driven luminosity from the neutron-star surface, so that ($L-L_a$) is the excess luminosity due to the thermonuclear flash. The initial decline is well fitted by an exponential decay (dashed line) with a time constant of $\tau \simeq 3$ s. However, for times greater than ~20 s after the burst peak, the decay time scale becomes much longer; 100 s after the peak, the local best-fit time constant is $\tau \simeq 60$ s. This "tail" of relatively soft X-rays (blackbody temperature $\simeq 1.3 \times 10^7$ K) contains ~10% of the total burst emission. These properties are in good agreement with those of soft X-ray "tails" in many observed X-ray burst sources. (From Joss 1980.)

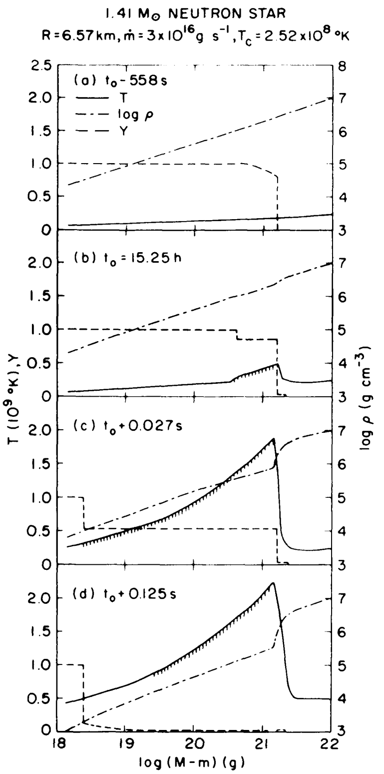

Figure 7. Structure of the surface layers of model 1 by Joss (1978) prior to and during the first helium-burning flash, which begins near time t_0. M is the total mass of the neutron star and m(r) is the mass enclosed within a sphere of radius r, with r = 0 at the stellar center; thus (M-m) is the total mass of the surface layers above level r. T is the temperature (left-hand scale), ρ the density (right-hand scale), and Y the fractional abundance of helium by mass (left-hand scale). The hatched regions indicate the extent of the convection zone generated by the flash. (a) Just prior to the flash; (b) near the start of the flash; (c) at the time when ~50% of the available fuel has been consumed; and (d) near the time of peak shell-burning temperature and peak surface luminosity. (From Joss 1978.)

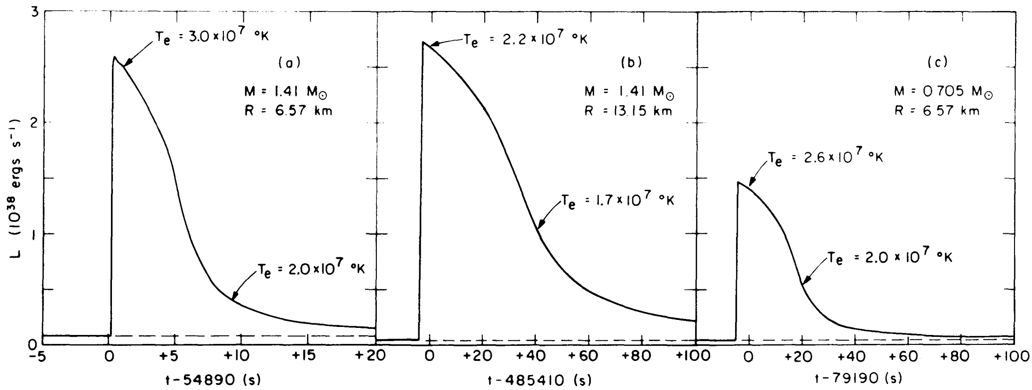

Figure 8. Temporal evolution of the first X-ray burst from model 1 by Joss (1978), with neutron-star mass M = 1.41 $M_\odot$ and radius R = 6.57 km. The notation is the same as in Figure 5. (b) Same as (a), but for a model by Joss and Li (1980) which has the same parameters as model 1 except that R = 13.15 km. (c) Same as (a), but for a model by Joss and Li (1980) which has the same parameters as model 1 except that M = 0.705 $M_\odot$. Note the difference in the scale of time for (b) and (c) compared to that of (a). The differences among these three models can be largely explained by simple scaling arguments (see text). (From Joss and Li 1980.)

Finally, the time scale (τ_D) of decline of surface X-ray emission following a flash is roughly directly proportional to the energy released in a flash, which is in turn directly proportional to τ_R and inversely proportional to the rate (L_{max}) at which that energy escapes the star; thus,

$$\tau_D \sim \tau_R/L_{max} \sim R^4 M^{-2}. \qquad (3)$$

Joss and Li (1980) carried out numerical computations of the evolution of the helium-burning shell for neutron stars with a few different masses and radii (see Figure 8) and fitted their results for τ_R, L_{max}, and τ_B to power-law expressions in M and R. They obtained

$$\tau_R^{(fit)} \sim R^{3.1} M^{-0.5} \quad ;$$

$$L_{max}^{(fit)} \sim R^{0.1} M^{0.8} \quad ; \qquad (4)$$

$$\tau_D^{(fit)} \sim R^{3.1} M^{-1.4} \quad .$$

These expressions are in reasonably good agreement with relations (1)-(3). The existence of these simple scaling relations suggests the intriguing possibility that once the physics of neutron-star thermonuclear flashes is sufficiently well understood, it may be possible to deduce information on the masses and radii of neutron stars from the observed properties of X-ray bursts that result from such flashes. (As noted by Joss and Li, however, these scaling relations should not be applied to the observational data until the remaining major uncertainties in the theoretical calculations have been resolved.) The indirect measurement of general relativistic effects from the burst properties may be even more powerful in this regard (see §V below).

Joss and Li (1980) also investigated the evolution of the helium-burning shell in models wherein the effects of an intense surface magnetic field upon the surface layers were taken into account. They argued that if the magnetic field is sufficiently strong to funnel the accretion onto the magnetic polar caps of the neutron star, then the effective accretion rate in the polar cap regions is enhanced by a factor of $\sim 10^3$ (for a fixed total accretion rate $\dot{m}$) and the instability of the nuclear burning shells should be reduced (see also Taam and Picklum 1978 and Joss 1978). The surface magnetic field strength, B, required to funnel the accretion is not well determined, but available estimates (see, e.g., Arons and Lea 1980) yield $B \simeq 10^{12}$ G. Joss and Li (1980) found that surface magnetic fields in excess of $\sim 10^{12}$ G will also have some significant effects upon the heat transport properties of the surface layers, but none of these effects are likely to be as important as the funneling of the accretion flow.

It has become increasingly clear that hydrogen burning can have a major influence on the behavior of the helium-burning shell (Taam and Picklum 1978; Czerny and Jaroszyński 1979; Ergma and Tutukov 1980). The saturation of the CNO cycle by the finite lifetimes of the beta-unstable nuclei that participate in the cycle limits the hydrogen-burning rates to such an extent that, at higher accretion rates ($\gtrsim 1 \times 10^{16}$ g s^{-1}), the hydrogen-burning shell is forced inward until it overlaps the helium-burning shell. Taam and Picklum (1979) and Taam (1980) have carried out the first fully time-dependent computations of the evolution of the surface layers of a neutron star with a hydrogen-burning shell included and found that the hydrogen- and helium-burning shells can, indeed, interact in a complex way (see Figure 9). In fact, in their models the heating of the accreted material by the neutron-star core prior to a thermonuclear flash was insignificant compared to the heating that resulted from hydrogen burning. However, this effect appears to have been a consequence of the low core temperatures chosen for the neutron star ($<10^8$ K); such cores would generally not be in thermal equilibrium with the nuclear burning shells, but they might represent the properties of an old neutron star that has begun to accrete matter during the past $\sim 10^{2-3}$ yr.

Fujimoto, Hanawa, and Miyaji (1980) have also studied the interaction between the hydrogen- and helium-burning shells. They argued

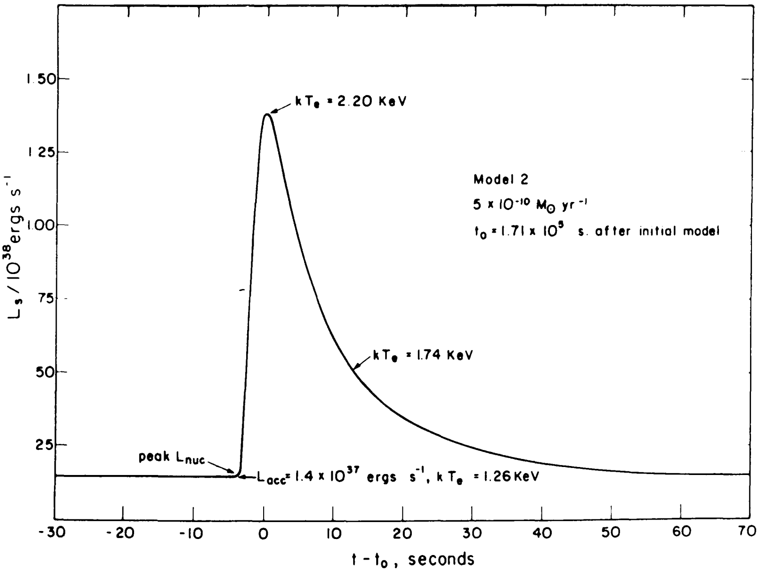

Figure 9. The behavior of the surface luminosity L_s following a thermonuclear flash in model 2 by Taam (1980). The parameters of the model are indicated in the figure. The accreting material is assumed to have an initial heavy-element abundance of 0.004 by mass. Time t = 0 is at the start of accretion onto the neutron-star surface, L_{acc} is the level of persistent accretion-driven luminosity, and the effective temperature (T_e) is indicated at a few points. The flash is driven by helium burning, but the entrainment of hydrogen into the flash has a strong effect upon its properties (see text). (From Taam 1980.)

that for neutron stars with low core temperatures there will be three modes of thermonuclear flashes: helium flashes followed by simultaneous helium burning and hydrogen burning when the two shells overlap at high accretion rates, pure helium flashes at intermediate accretion rates, and hydrogen flashes that ignite the helium-burning shell at low accretion rates. However, we note that due to the saturation of the CNO cycle, the rise in temperature ΔT due to a hydrogen flash is limited to

$$\Delta T \lesssim 10^8 \text{ K} \left(\frac{X_{CNO}}{10^{-2}} \right) , \tag{5}$$

where X_{CNO} is the fractional abundance by mass of CNO nuclei (Ayasli and Joss 1980). Hence, it seems that unless the abundances of the CNO nuclei in the accreting matter are substantially higher than their cosmic abundances, a hydrogen flash will usually be unable to fully ignite the helium shell and the third scenario described by Fujimoto et al. will not be realized. Nonetheless, it has become evident from all of the above work that the interactions between the hydrogen- and helium-burning shells may be very complex; it is highly likely that still further complications will be uncovered by future work.

Taam and Picklum (1978) studied the thermal evolution of a carbon-burning shell in an accreting neutron star but did not carry out their computations through a complete thermonuclear flash. Their models again assumed low core temperatures ($<10^8$ K) that would not be in thermal equilibrium with the surface nuclear burning shells.

V. GENERAL RELATIVISTIC EFFECTS

Utilizing the assumption that the spectra of X-ray bursts following peak luminosity could be represented by blackbodies, Van Paradijs (1978) demonstrated that in many cases the scale size of the X-ray emitting region is nearly constant; if the emitting region is a spherical surface, then its radius is ~7 km. This result lends compelling support to the idea that many X-ray bursts are thermal emission from the photospheres of neutron stars, and thus provides indirect evidence in favor of the thermonuclear flash model for such bursts.

However, it has become apparent that this argument is complicated by general relativistic corrections, such as the effect of gravitational redshift and time dilation upon the X-radiation emitted by the neutron-star photosphere (Goldman 1979; Van Paradijs 1979). The importance of general relativity can be seen by inspection of the parameter

$$\frac{2GM}{Rc^2} \simeq 0.60 \left(\frac{M}{1.4\ M_\odot} \right) \left(\frac{R}{7\ \text{km}} \right)^{-1} . \tag{6}$$

The left-hand side of equation (7) is just the ratio of the Schwarzschild radius of the neutron star ($2GM/c^2$) to its actual radius. For the indicated values of M and R, which have been used in many of the actual model calculations of thermonuclear flashes, it is evident that this parameter is not very much smaller than unity, so that general relativistic effects should be substantial.

It was shown by Goldman (1979) and Van Paradijs (1979) that when general relativistic corrections are included in determinations of the luminosities and effective blackbody temperatures of X-ray bursts, one obtains, at least in principle, strong constraints on the masses and radii of the underlying neutron stars. If taken at face value, these constraints would, in turn, severely constrain the equation of state of matter at densities in excess of nuclear-matter densities ($\rho > 2 \times 10^{14}$ g cm^{-3}). However, such constraints cannot yet be taken seriously, as other complications, including possible violations of spherical symmetry (see §VII) and deviations of the emitted spectrum from a simple blackbody (Swank, Eardley, and Serlemitsos 1979; Van Paradijs, Rybicki, and Lamb 1980), may turn out to be important. Once these additional complexities have been untangled, the observed properties of X-ray bursts may prove to be a powerful probe of the basic properties of neutron stars.

General relativistic corrections to the equations of stellar structure and evolution may also play a significant role in determining the behavior of the thermonuclear flashes themselves. Some of these corrections have already been included in some calculations (e.g., those by Taam and Picklum 1978, 1979; Czerny and Jaroszyński 1979; and Taam 1980). However, no fully time-dependent model computations have yet included all of the relevant general relativistic corrections.

VI. COMPARISON WITH OBSERVATIONAL PHENOMENA

A. X-Ray Bursts

The results of the numerical calculations of thermonuclear flashes (see Figures 4-9) strongly support the conjecture that the bursts from most observed X-ray burst sources result from such flashes. In particular, the typical burst rise times, decay time scales, peak luminosities, total emitted energies, spectral properties, low-energy "tails," and recurrence intervals (see Lewin and Clark 1980; Lewin and Joss 1980) are reproduced remarkably well by such flashes.

However, there are some difficulties with this model. It does not reproduce the observed complex burst structures and recurrence patterns, which vary from one burst source to another and often vary with time in a single source. It is quite possible that these complexities will be better understood when some of the approximations of the present model calculations are relaxed; we shall return to this point in §VII.

A particulary severe problem for the nuclear flash model is the ratios, α, of time-averaged persistent X-ray luminosity to time-averaged burst luminosity from the observed burst sources. In this model, α should just be the ratio of the gravitational energy released by accretion (more or less continuously) to the nuclear energy released in the flashes. For helium-burning flashes, the numerical value of α should thus be

$$\alpha \simeq 1 \times 10^2 \left(\frac{M}{M_\odot}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^{-1} \qquad (7)$$

(Joss 1977; Lamb and Lamb 1978). However, some burst sources have reported values of α significantly less than 10^2; one such case is 4U1608-52, which displayed two bursts separated by an interval of only ten minutes and a correspondingly small upper limit of $\alpha < 2.5$ during that interval (Murakami et al. 1980). Moreover, in some sources the recurrence intervals have been observed to increase (decrease) when the persistent luminosity increased (decreased), which is opposite to the trend expected from this model (see Figure 5).

If the nuclear flash model is correct, it is possible that the observed values of α are sometimes (perhaps always) reduced by the storage of nuclear fuel during burst-inactive phases (Lamb and Lamb 1978). Such a "battery" mechanism may be provided by large-scale violations of spherical symmetry, so that only a fraction of the surface of the neutron star participates in each flash, or from fluctuations resulting from the interaction between the hydrogen- and helium-burning shells (e.g., fluctuations in the amount of hydrogen entrained into the convection zone generated by a helium flash). Even in the absence of such fluctuations, the entrainment of hydrogen into a helium-burning flash could, in principle, reduce the value of α by up to a factor of ~5 (due to proton captures onto the heavier nuclei being synthesized and a concomitant increase in the energy yield per unit mass); the time-dependent calculations by Taam and Picklum (1979) and Taam (1980) do not indicate any reduction in α-values by this effect, but more complete hydrogen-burning reaction networks might yield different results (Wallace and Woosley 1980; Ergma and Kudrjashov 1980; Ayasli and Joss 1980). It is also possible that the accretion-driven luminosity is emitted anisotropically and/or largely shifted to photon energies $\lesssim$ 1 keV; Milgrom (1978) has proposed a specific mechanism (an accretion disk that extends all the way to the surface of a weakly magnetized neutron star) that could produce both these effects and thereby reduce the observed values of α by up to a factor of ~2.

B. The Rapid Burster

It is important to realize that the bursts from the "Rapid Burster," MXB1730-335, are at present unique and almost certainly cannot be the result of thermonuclear flashes. The recurrence intervals between bursts are $\sim 10^{1-3}$ s, and $\alpha \lesssim 2$ for this source (Lewin et al. 1976).

Hoffman, Marshall, and Lewin (1978) have described these bursts as "type II" and those from other sources as "type I". However, Hoffman, Marshall, and Lewin also found that the Rapid Burster occasionally emits "special" bursts whose properties much more closely resemble the type I bursts from other sources. Moreover, the ratio of time-averaged luminosity in the type II bursts from the Rapid Burster to that in its type I bursts is $\sim 10^2$ (Hoffman, Marshall, and Lewin 1978). Hoffman, Marshall, and Lewin made the intriguing speculation that the type I bursts from the Rapid Burster are the result of thermonuclear flashes on an accreting neutron star, while the type II bursts are the result of an unstable accretion flow onto the same object.

C. The Fast X-Ray Transients

The morphology of some of the "fast X-ray transients", which have durations of $\sim 10^{2-3}$ s, is suggestively similar to that of ordinary type I X-ray bursts (Hoffman et al. 1978). Joss (1979b) suggested that the fast transients may be the result of helium-burning flashes relatively deep within the surface layers of slowly accreting neutron stars ($\dot{m} \lesssim 10^{15}$ g s^{-1}). If this picture is correct, one would expect outbursts from the fast transients to recur, but only on time scales of weeks or longer. Some fast transients have been observed to have distinct precursors, consisting of relatively brief but intense X-ray emission just before the start of the main burst (Hoffman et al. 1978); a low accretion rate should result in a relatively large temperature contrast between the nuclear flashing shell and the outermost surface layers of the neutron star, so that the precursors might be the result of shock heating of the outer surface layers. However, detailed numerical computations of deep helium-burning flashes have yet to be carried out, and in the interim the above scenario must be regarded as highly speculative.

D. Relation to Binary X-Ray Pulsars and the Ages of Burst Sources

Let us accept, for the sake of discussion, that most observed X-ray burst sources can be understood as accreting neutron stars that are undergoing thermonuclear flashes. Since X-ray pulsars are also widely believed to be accreting neutron stars, it is then puzzling, at first sight, that these objects do not also display bursting behavior. However, the strong magnetic field ($\gtrsim 10^{12}$ G; see Arons and Lea 1980) that funnels the accretion onto the magnetic polar caps of an X-ray pulsar will also enhance the efficiency of radiative and conductive heat transport within and above its nuclear burning shells. Even more importantly, the heat released by accretion will have a much greater influence upon the inner burning shells if the freshly accreted matter is confined to the polar caps, rather than spread uniformly over the neutron-star surface. These effects should tend to reduce the instability of the nuclear burning shells of an X-ray pulsar against thermonuclear flashes (Taam and Picklum 1978; Joss 1978; Joss and Li 1980). Evolutionary models of the helium-burning shell in the presence of an intense magnetic field confirm the assertion that such fields reduce the instability of the shell (Joss and Li 1980).

With this picture, we can also understand why the persistent X-ray flux from type I X-ray burst sources is unpulsed: those neutron stars whose magnetic fields are too weak to funnel the accreting matter may be precisely those that can undergo thermonuclear flashes (Taam and Picklum 1978; Joss 1978; Joss and Li 1980). If the magnetic field was originally as strong as in an X-ray pulsar but has since decayed, then the neutron star must be fairly old (probably older than 10^7 yr; see Ruderman 1972 and references therein; Flowers and Ruderman 1977). The lack of X-ray eclipses in burst sources may also reflect membership in relatively old binary systems (Joss and Rappaport 1979) and may result from X-ray beaming effects that set in after the neutron-star magnetic field has decayed (see, e.g., Milgrom 1978). The concentration of X-ray burst sources in the direction of the galactic center and the identification of several of them with globular clusters (see Figure 1) may well be other manifestations of membership in an older galactic population than the X-ray pulsars, which are distributed through the disk of the galaxy and whose binary companion stars are often of early spectral type.

E. Gamma-Ray Burst Sources

Woosley and Taam (1976) suggested that carbon-burning flashes on accreting neutron stars result in cosmic γ-ray bursts. A more detailed look at the heat transport properties of the neutron-star surface layers demonstrates that the rising convective elements above any nuclear burning shell would cool to temperatures $\ll 10^{10}$ K before reaching the photosphere (Joss 1977). However, it is possible that under some circumstances, a thermonuclear flash generates dynamical effects in the outermost surface layers of a neutron star, resulting in the emission of a gamma-ray burst (see, e.g., Ruderman 1980).

VII. CONCLUDING REMARKS

We have just begun to grasp all of the intricacies of nuclear processes in the surface layers of accreting neutron stars. The theoretical problems are fascinating, not only as investigations in fundamental physics, but also for their probable applications to X-ray burst sources and other observational phenomena and as a potentially powerful tool for probing the basic properties of neutron stars.

The only complete evolutionary computations of neutron-star thermonuclear flashes that have been carried out to date (Joss 1978; Taam and Picklum 1979; Joss and Li 1980; Taam 1980) relied on a number of simplifying assumptions and approximations, such as the neglect of some general relativistic effects (see §V), the assumption of spherical symmetry, the neglect of possible dynamical effects, and, in some cases, the assumption that the neutron-star core is in thermal equilibrium. These approximations will have to be relaxed in future studies before this phenomenon and its observational implications can be more fully understood.

Small but significant violations of spherical symmetry might result from accretion through a relatively weak ($\lesssim 10^{11}$ G) magnetic field or the residual angular momentum of the accreting matter. If thermonuclear flashes result in X-ray bursts, such violations could be the key to the observed complexities in burst structure and recurrence patterns (see Lewin and Clark 1980; Lewin and Joss 1980). For example, a thermonuclear flash that ignites on one portion of the neutron-star surface may propagate around the star, in a pattern that varies from flash to flash and from one star to another (Joss 1978). A thorough investigation of such possibilities will eventually require two- or three-dimensional numerical computations, which will be much more difficult than the computations of spherically symmetric models that have been attempted to date.

Complexities in radiative transfer in the outer surface layers of the neutron star and possible mass ejection from the photosphere near the peak of a burst may also substantially complicate the observational properties of X-ray bursts and render their physical interpretation much more difficult. Some preliminary results on deviations from blackbody emission by a hot neutron-star atmosphere have been reported (Swank, Eardley, and Serlemitsos 1979; Van Paradijis, Rybicki, and Lamb 1980), but much work in these areas remains to be done.

The importance of thermal equilibrium of the neutron-star core has been only tentatively explored (see Figure 4). If there is a change in the average accretion rate, the thermal inertia of the core is sufficient to require the elapse of $\sim 10^{2-3}$ yr for thermal equilibrium to be reestablished (Lamb and Lamb 1978). Thus departures from thermal equilibrium are entirely possible, and they could have a substantial effect upon the behavior of the nuclear burning shells.

Many of these issues can be attacked by additional calculations in the immediate future. Further progress, and more surprises, are bound to be forthcoming.

ACKNOWLEDGEMENTS

I am grateful to S. Ayasli for helpful discussions. Earlier versions of some portions of this review were previously published in *Comments on Astrophysics*, *8*, 109 (1979), *Annals of the New York Academy of Sciences*, *336*, 479 (1980), and *Space Science Reviews* (in collaboration with W.H.G. Lewin; in press). This work was supported in part by the National Science Foundation under grant AST78-21993 and by the National Aeronautics and Space Administration under contract NAS5-24441 and grant NSG-7643.

REFERENCES

Arons, J., and Lea, S.M. 1980, *Astrophys. J.*, *235*, 1016.

Ayasli, S., and Joss, P.C. 1980, manuscript in preparation.

Barranco, M., Buchler, J.R., and Livio, M. 1980, preprint.

Cowie, L.L., Ostriker, J.P., and Stark, A.A. 1978, *Astrophys. J.*, *226*, 1041.

Czerny, M., and Jaroszyński, M. 1979, submitted to *Acta Astronomica*.

Ergma, E.V., and Kudrjashov, A.D. 1980, preprint.

Ergma, E.V., and Tutukov, A.V. 1980, *Astron. Astrophys.*, *84*, 123.

Flowers, E., and Ruderman, M. 1977, *Astrophys. J.*, *215*, 302.

Fujimoto, M., Hanawa, T., and Miyaji, S. 1980, preprint.

Giacconi, R., Gursky, H., Kellogg, E., Schreier, E., and Tananbaum, H. 1971, *Astrophys. J. (Letters)*, *167*, L67.

Giannone, P., and Weigert, A. 1967, *Zs. Astrophys.*, *67*, 41.

Goldman, Y. 1979, *Astron. Astrophys.*, *78*, L15.

Grindlay, J., Gursky, H., Schnopper, D., Parsignault, R., Heise, J., Brinkman, A.C., and Schrijver, J. 1976, *Astrophys. J. (Letters)*, *205*, L127.

Hansen, C.J., and Van Horn, H.M. 1975, *Astrophys. J.*, *195*, 735.

Hoffman, J.A., Lewin, W.H.G., Doty, J., Jernigan, G., Haney, M., and Richardson, J.A. 1978, *Astrophys. J. (Letters)*, *221*, L57.

Hoffman, J.A., Marshall, H.L., and Lewin, W.H.G. 1978, *Nature*, *271*, 630.

Hoshi, R. 1980, preprint.

Joss, P.C. 1977, *Nature*, *270*, 310.

Joss, P.C. 1978, *Astrophys. J. (Letters)*, *225*, L123.

Joss, P.C. 1979a, *Comments on Astrophys.*, *8*, 109.

Joss, P.C. 1979b, in "Compact Galactic X-ray Sources," ed. D. Pines and F. Lamb (Urbana, Illinois: Physics Dept., Univ. of Illinois), p. 89.

Joss, P.C. 1980, *Annals N.Y. Acad. Sci.*, *336*, 479.

Joss, P.C., and Li, F.K. 1980, *Astrophys. J.*, *238*, 287.

Joss, P.C., and Rappaport, S.A. 1979, *Astron. Astrophys.*, *71*, 217.

Lamb, D.Q., and Lamb, F.K. 1977, *Annals N.Y. Acad. Sci.*,*302*, 261.

Lamb, D.Q., and Lamb, F.K. 1978, *Astrophys. J.*, *220*, 291.

Lewin, W.H.G., and Clark, G.W. 1980, *Annals N.Y. Acad. Sci.*, *336*, 451.

Lewin, W.H.G., Doty, J., Clark, G.W., Rappaport, S.A., Bradt, H.V.D., Doxsey, R., Hearn, D.R., Hoffman, J.A., Jernigan, J.G., Li, F.K., Mayer, W., McClintock, J., Primini, F., and Richardson, J. 1976, *Astrophys. J. (Letters)*, *207*, L95.

Lewin, W.H.G., and Joss, P.C. 1977, *Nature*, *270*, 211.

Lewin, W.H.G., and Joss, P.C. 1980, *Space Sci. Revs.*, in press.

Lewin, W.H.G., McClintock, J.E., and Ricker, G.R. 1971, *Astrophys. J. (Letters)*, *169*, L17.

Maraschi, L., and Cavaliere, A. 1977, in "Highlights of Astronomy," Vol. 4, ed. E.A. Müller (Dordrecht: Reidel), Part I, p. 127.

Milgrom, M. 1978, *Astron. Astrophys.*, *67*, L25.

Murakami, T., Inoue, H., Koyama, K., Makishima, K., Matsuoka, M., Oda, M., Ogawara, Y., Ohashi, T., Shibazaki, N., Tanaka, Y., Tawara, Y., Hayakawa, S., Kunieda, H., Makino, F., Masai, K., Nagase, F., Miyamoto, S., Tsunemi, H., Yamashita, K., and Kondo, I. 1980, submitted to *Nature*.

Rosenbluth, M.N., Ruderman, M., Dyson, F., Bahcall, J.N., Shaham, J., and Ostriker, J. 1973, *Astrophys. J.*, *184*, 907.
Ruderman, M. 1972, *Ann. Rev. Astron. Astrophys.*, *10*, 427.
Ruderman, M. 1980, talk presented at the Erice School, to be published.
Schreier, E., Levinson, R., Gursky, H., Kellogg, E., Tananbaum, H., and Giacconi, R. 1972, *Astrophys. J. (Letters)*, *172*, L79.
Schwarzschild, M., and Härm, R. 1965, *Astrophys. J.*, *142*, 855.
Swank, J.H., Eardley, D.M., and Serlemitsos, P.J. 1979, preprint.
Taam, R.E. 1980, preprint.
Taam, R.E., and Picklum, R.E. 1978, *Astrophys. J.*, *224*, 210.
Taam, R.E., and Picklum, R.E. 1979, *Astrophys. J.*, *233*, 327.
Tananbaum, H., Gursky, H., Kellogg, E.M., Levinson, R., Schreier, E., and Giacconi, R. 1972, *Astrophys. J. (Letters)*, *174*, L143.
Van Horn, H.M., and Hansen, C.J. 1974, *Astrophys. J.*, *191*, 479.
Van Paradijs, J. 1978, *Nature*, *274*, 650.
Van Paradijs, J. 1979, *Astrophys. J.*, *234*, 609.
Van Paradijs, J., Rybicki, G., and Lamb, D.Q. 1980, talk presented at the Meeting of the High Energy Astrophysics Division of the American Astronomical Society, Cambridge, Massachusetts, January 1980, abstract in *Bull. Amer. Astron. Soc.*, *11*, 788 (1979).
Wallace, R.K., and Woosley, S.E. 1980, preprint.
Woosley, S.E., and Taam, R.E. 1976, *Nature*, *263*, 101.

DISCUSSION

Sugimoto: In the case of accreting white dwarfs, shell burning is ignited even when the core temperature is absolute zero at the onset of the accretion. What about the case of accreting neutron stars?

Joss: If the core temperature is less than about 10^8K, then the core is unimportant in heating the surface layers. However, as shown by the work of Taam and Picklum (1978), and Fujimoto, Hanawa, and Miyaji (1980), thermonuclear flashes will still occur even if the core is "cold" in this sense.

Tutukov: What heats the accretion shell between flashes, the hot neutron star or gravitational compression?

Joss: If the core of the neutron star is in thermal equilibrium with the nuclear burning shells, then under many, if not all, conditions of interest the heat stored in the core is more important than gravitational compression in heating the surface layers between flashes.

Sugimoto: You have shown a diagram of the core temperature against the accretion rate, on which there is only one line relating these two quantities. In the case of accreting white dwarfs, we can consider any point in that diagram, depending on the initial conditions. What determines that line in your case? If you claim it to be a limit cycle, what is the reason?

Joss: The equilibrium core temperature of an accreting neutron star was first estimated by Lamb and Lamb (1978); I incorporated a modified version of their estimate into my own model computations. More accurate calculations, currently underway, suggest that the earlier estimates of equilibrium core temperatures were too high, but not by a large factor.

Lamb: The recent investigation by Fujimoto, Miyaji, and Hanawa (1980) and the recent numerical calculations by Taam (1980) show unstable He burning at high accretion rates, in contrast to your own calculations (Joss 1978). This issue is important, as you point out, in trying to understand the distinction between the X-ray bursters and the pulsating X-ray sources such as Her X-1, Cen X-3, and SMC X-1, which apparently do not burst. What accounts for the difference between their results and yours, and which do you think represents more correctly the behavior of the burning at high accretion rates?

Joss: The difference, I believe, is a result of the high core temperature T_c, at high accretion rates that we assumed in our calculations, in contrast to the low values of T_c employed by Fujimoto et al. (1980). The values we adopted were based on the estimated conditions for thermal equilibrium of the core by Lamb and Lamb (1978), as modified by Joss (1978). As already remarked we are presently carrying out more accurate calculations of thermal equilibrium conditions and our preliminary results suggest that the original estimates of T_c were too high, but not by a very large factor. I therefore think that the burning will, indeed, be largely stabilized at high accretion rates, provided that the core is in thermal equilibrium.

Sugimoto: What are the important effects of general relativity other than "increasing" the gravity?

Joss: General relativistic effects enter the equations of stellar structure and evolution in a highly complex and nonlinear way (Thorne 1977 and references therein). As I indicated in my talk, certain results may be accounted for in terms of some particular general relativistic effect, such as time dilation or gravitational redshift. However, I know of no general way to isolate all of the possible effects of general relativity; one must simply incorporate the appropriate corrections into a detailed computation and see what emerges.

Schatzman: What kind of increased rate factor did you take for thermonuclear reactions in dense matter?

Joss: In our earliest calculations, we neglected screening corrections to the thermonuclear reaction rates. This is not very restrictive approximation since the screening corrections do not greatly change the temperature or density-dependence of the reaction rates and, as pointed out by Dr. Sugimoto in his talk earlier this morning, the absolute values of the reaction rates are much less important than their temperature dependences in determing the behavior of the nuclear burning shells. In our more recent calculations, we have incorporated the weak and strong screening corrections of Salpeter and Van Horn (1969).

Lamb: The helium flash calculations for nuclear burning on accreting neutron stars give values of α, the ratio of the background (accretion) luminosity to the time averaged burst luminosity in the range 200-800 (cf. Joss 1978, Joss and Li 1979, Taam and Picklum 1979, Taam 1980) and show all of the helium and hydrogen being consumed. However, early observations of MXB1743-28 by SAS-3 (Lewin 1977) indicated, and more recent observations of 1608-522 by Hakucho (Inoue *et al.* 1980) have shown clearly that some Type I burst sources exhibit $\alpha \lesssim 2\text{-}3$. Earlier, we had suggested on the basis of the SAS-3 observations that in some cases all the nuclear fuel must not be exhausted in a given flash, and that some type of "battery" model seems to be required (Lamb and Lamb 1978). Would you comment on this?

Joss: I fully agree with you that, in view of the clear observation by Inoue et al. of two Type I bursts from 1608-522 separated by only about 10 minutes, we must now take seriously the need for some of a "battery" idea to account for this phenomenon. However, I doubt that this will be a severe problem for the thermonuclear flash model. First, occurrences of Type I bursts in rapid succession seem to be quite rare and isolated, and their explanation may not play a central role in our understanding of the burst phenomenon. Second, the entrainment of hydrogen into the thermonuclear flashes, when fully taken into account, might already reduce the theoretical α-values to as low as ~10 even in the absence of a "battery" mechanism. As far as possible "battery" models are concerned, two thoughts come to mind: violations of spherical symmetry, so that less than the entire surface of the neutron star participates in a flash and some nuclear fuel is saved for the next flash; and fluctuations in the extent of the convection zone generated by each flash and in the resultant amount of nuclear fuel entrained in the flash. However, any such explanation must, of course, be regarded as highly speculative until it is supported by serious calculations.