6. X-RAY AND GAMMA-RAY BURSTERS

https://doi.org/10.1017/S0252921100086139 Published online by Cambridge University Press

X-Ray Burst Sources

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ABSTRACT

Type I cosmic X-ray bursts are widely thought to result from thermonuclear flashes in the surface layers of accreting neutron stars. The thermonuclear-flash model is able to account for a wide variety of observed burst phenomena. However, a number of theoretical and observational problems persist. Foremost among these are related to the existence of apparent luminosities in excess of the Eddington limit in many observed bursts. Under circumstances of very high luminosity, the theoretical treatment of radiative transfer and radiatively driven mass loss at the neutron-star surface becomes complex. We discuss the current status of theoretical work in this area and the prospects for developing an understanding of the remaining phenomenological problems: (a) What is the nature of the precursor in some fast transients and of the twin-peak structure observed in some shorter bursts? (b) Do some bursts actually achieve super-Eddington luminosities, and if so, how? (c) What are the characteristics of quasi-static mass loss in the presence of such luminosities? (d) How is the color temperature related to the effective temperature? and, (e) What are the implications concerning the Galactic distance scale?

I. INTRODUCTION

X-ray bursts were discovered (independently) by GRINDLAY *et al.* [1,2] and BELIAN *et al.* [3,4] in 1975. Since then, about 37 X-ray burst sources have been identified (see MATSUOKA [5] for a recent list). The observed properties of these sources have been extensively reviewed by LEWIN and JOSS [6,7], and JOSS and RAPPAPORT [8]. The salient features

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of X-ray bursts include burst rise times of ~ 1 [s], decay time scales of $\sim 3 - 100$ [s], peak luminosities of $\sim 10^{38}$ [erg s^{-1}], and total emitted energies of $\sim 10^{39}$ [ergs] per burst (see Fig. 1). The spectra of X-ray bursts can generally be well fitted by blackbody emission from a surface with a peak temperature of $\sim 3 \times 10^7$ [K] (Fig. 2) and a roughly constant scale size that corresponds, for a spherical surface, to a radius of ~ 10 [km] (if general relativistic effects are neglected). 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, α, is typically $\sim 10^2$ during burst-active phases.

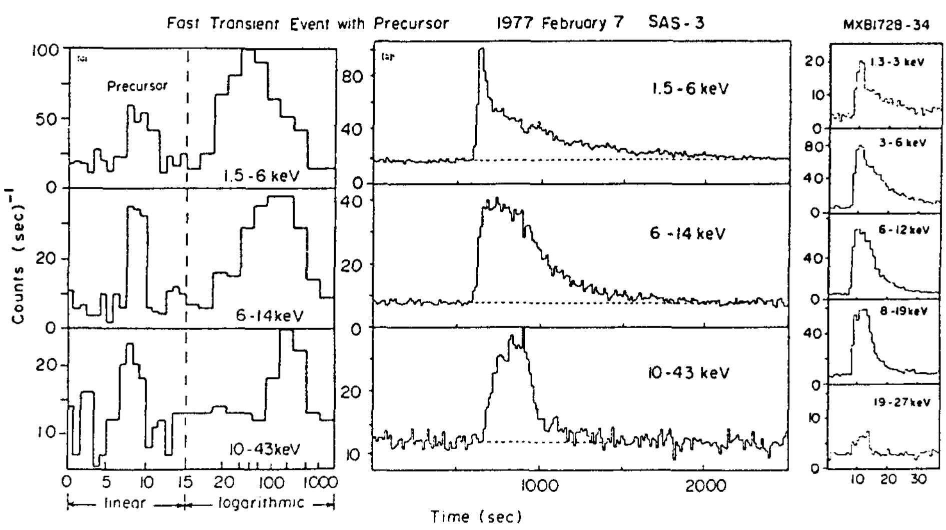

Figure 1: *(a and b) Profiles of the 1977 February 7 fast X-ray transient (a long Type I X-ray burst), which lasted $\sim$ 1500 s. The precursor is not visible in (b) because of the summing of the data into coarse time bins. (c) Composite profile of type I X-ray bursts from MXB 1728-34. This figure is from* HOFFMAN *et al.* [9].

The properties of the Rapid Burster, MXB 1730-335, are different from those of all other known burst sources [6,7]. The recurrence intervals between the rapid bursts are $\sim 10^1 - 10^3$ [s] when the source is active, and on at least one occasion α was less than ~ 0.2 [11]. HOFFMAN *et al.*

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[12] have described these bursts as "type II" and those from other sources as "type I." However, Hoffman *et al.* also found that the rapid burster occasionally emits "special" bursts whose properties much more closely resemble the type I bursts from other sources. Hoffman *et al.* made the intriguing speculation that type I bursts from the rapid burster are the result of thermonuclear flashes on an accreting neutron star (see Section II), while the type II bursts are the result of an unstable accretion flow onto the same object. A brief review of possible accretion instabilities that might be applicable to the rapid burster is given by LEWIN and JOSS [6,7]. In the remainder of this review, we shall discuss only those features that are relevant to the type I X-ray burst sources.

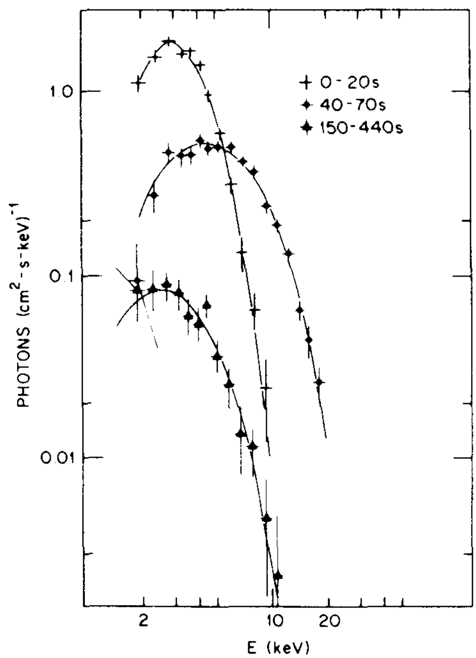

Figure 2: *Average spectra, in three time intervals, of a very long (~ 600 s) Type I X-ray burst from XB 1724-30, which is probably the burst source located in Terzan 2. Time zero is near the burst onset. The solid curves show the best fits to blackbody spectra. The values for* kT *are* ~ 0.9 [keV] (0-20 [s]), ~ 2.3 [keV] (40-70 [s]) *and* ~ 1.2 [keV] (150-440 [s]). *Under the assumption of a spherical emitting surface and a source distance of* 10 [kpc], *the best-fit blackbody radii were* ~ 100 [km] *during the first* 20 [s] *of the burst and* ~ 15 [km] *during the remainder of the burst. This figure is from* SWANK *et al.* [10].

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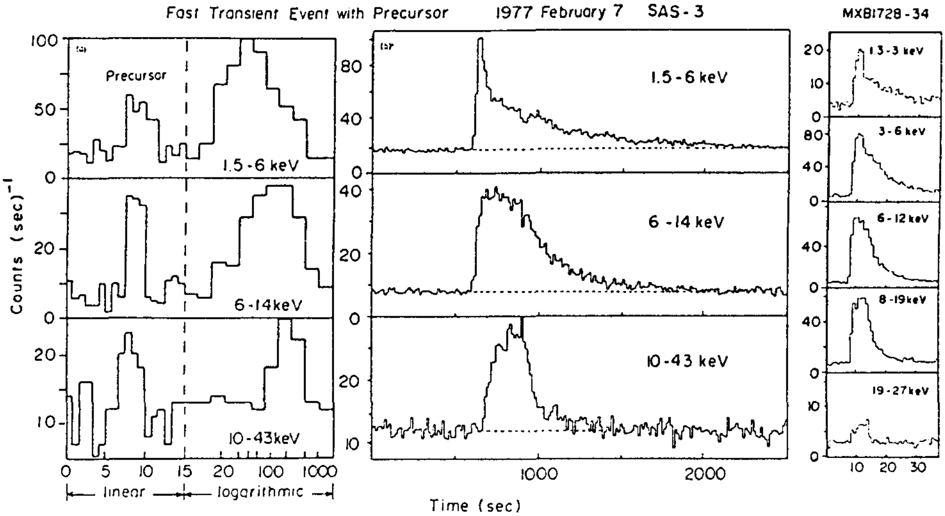

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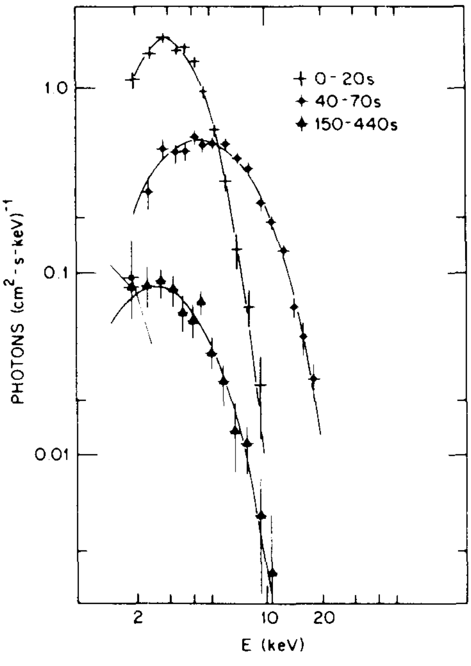

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The distribution of burst sources on the celestial sphere (Fig. 3) is strongly reminiscent of stellar Population II, with a strong concentration in the direction of the Galactic center. In fact, 9 of the burst sources have been found to lie in the direction of globular clusters. This situation contrasts sharply with that of the X-ray pulsars (also shown in Fig. 3), which appear to be more uniformly distributed through the Galactic disk and whose optical companion stars are often quite massive, suggesting association with a young stellar population.

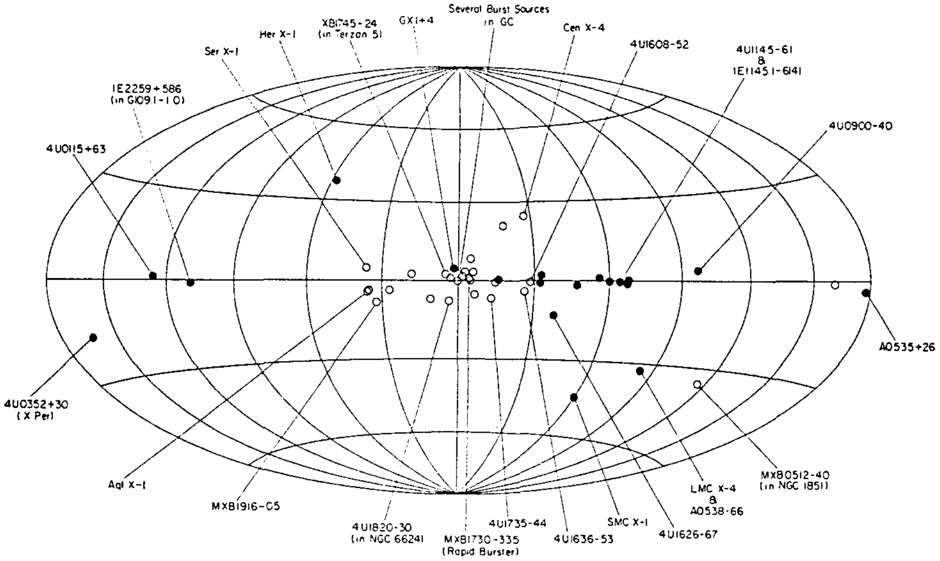

Figure 3: *Sky map, in Galactic coordinates, of 21 binary X-ray pulsars (•) and 27 X-ray burst sources (○) for which reasonably accurate positional determinations are available* [8]. *Some of the more important members of each class are identified. Some burst sources are located in globular clusters, as indicated. The tendency of the X-ray pulsars to be distributed along the Galactic equator and the concentration of X-ray burst sources toward the Galactic center are both apparent.*

The optical counterparts of the burst sources, where they have been identified at all, are found to be faint, blue objects with spectra that are dominated by emission lines (see [13] for references). Thus, the burst sources appear to be members of the larger class of Galactic bulge X-ray sources, whose optical and persistent X-ray emission share the same properties. The faintness of the optical counterparts of most Galactic bulge X-ray sources (including burst sources) rules out giant, supergiant, and early-type main sequence stars (see [6,7] and references therein). The optical properties are consistent with the idea that all of these sources are close-binary stellar systems containing collapsed objects, such as neutron stars, and (with perhaps only a few exceptions) intrinsically faint, low-mass ($\lesssim 0.5\ M_\odot$) main-sequence dwarf or degenerate dwarf companions [14]. It is, moreover, possible that such a companion could transfer sufficient mass to the collapsed star only if it nearly fills its critical potential lobe, in which case the orbital separation would be $\lesssim 10^{11}$ [cm] and the orbital period $\lesssim 0.3$ [days] (Fig. 4).

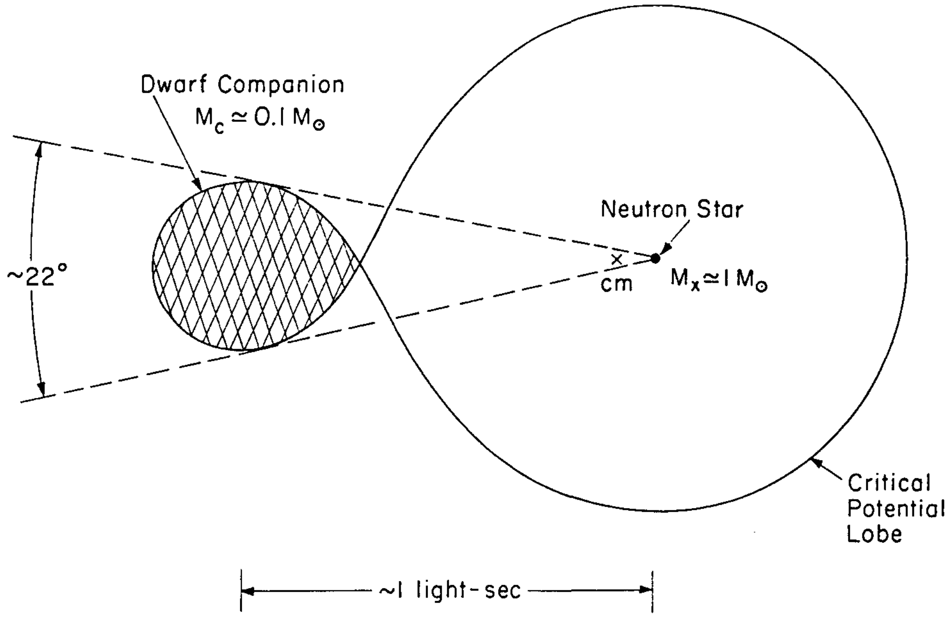

Figure 4: *Highly compact binary model for the Galactic bulge X-ray sources, including the X-ray burst sources. The figure is drawn to scale for the indicated illustrative values for the masses of the neutron star and companion star (M_X and M_C, respectively). Not shown is the accretion disk (surrounding the neutron star) which is thought to mediate the accretion flow. This figure is adapted from* JOSS and RAPPAPORT [14].

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The properties of such systems can be reconciled with the observational characteristics of most of the Galactic bulge sources [14]. In particular, the faintness of the optical counterparts is a natural consequence of the intrinsic faintness of the companion star; in fact, most of the very blue light that is seen results from reprocessing of X-radiation within the system, rather than from the intrinsic luminosity of the companion. Moreover, the assumed orbital separation is consistent with the short binary periods ($\sim$ 50 [min] to $\sim$ 8 [hr]) inferred from periodic absorption events in the persistent X-ray flux (see, e.g., [15,16,17]). An independent confirmation of the low-mass character of these systems comes from a relatively new approach to determine the mass of X-ray sources in globular clusters. As shown by BAHCALL and WOLF [18], the expectation value of the projected distance of an object of mass M from the center of a dynamically relaxed cluster of stars, each of mass m, is $0.7R_c(m/M)^{1/2}$ [arcsec]. In typical clusters, R_c is $\sim 5 - 10$ [arcsec]. GRINDLAY *et al.* [19], using the Einstein Observatory, determined the locations of eight X-ray sources located in globular clusters to an accuracy of several [arcsec]. They found that at the 90 per cent confidence level, the mass of each X-ray source lies between 1 and 5 solar masses under the assumptions that (i) the masses of all eight sources are about equal, (ii) the cluster cores are isothermal, and (iii) the masses of the cluster stars are approximately uniform ($\sim 0.5\ M_\odot$).

The collapsed objects in these low-mass binary systems are almost certainly neutron stars. Of course, the ability of the thermonuclear-flash model to explain many of the burst properties is very persuasive (see §II). However, there is substantial evidence in favor of neutron stars that is independent of the thermonuclear-flash model. Following an initial suggestion by SWANK *et al.* (see Fig. 2), VAN PARADIJS [20] showed that the burst sources, interpreted as blackbodies emitting isotropically, have roughly the same ratio of radiating surface area to average peak-burst luminosity. If the peak luminosities are assumed to be equal to the Eddington limit for a $1.4\ M_\odot$ object with a hydrogen envelope, the blackbody radii are found to have an average value of $\sim$ 8.5 [km]. (However, this argument becomes less clear cut when general relativistic effects are taken into account; see [8] and references therein.) For these reasons, it

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seems safe to conclude that Type I X-ray burst sources are neutron stars.

The prospects for improving our understanding of these sources have improved with the discovery of absorption dips in the burst spectra from MXB 1636-53 (WAKI *et al.* [21]). The most probable origin for these absorption features at 4.1 [keV] and 5.7 [keV] is the gravitationally redshifted K_α line and K edge of iron, respectively. If this interpretation is correct, it seems to indicate a radius for the collapsed object of only 1.6 times the Schwartzschild radius. This is just above the minimum radius for a stable neutron star with any equation of state (see [8] for references). However, before these observations can be used as reliable diagnostics of neutron-star properties, at least two questions need to be answered: (i) What is the mechanism for the line broadening? and (ii) Why are these absorption features not common to all bursts? It also remains to be seen how the redshift of these absorption lines is influenced by the transverse Doppler effect due to the rotation of the accreting material close to the neutron-star surface (see FUJIMOTO [52]).

II. THE THERMONUCLEAR FLASH MODEL

Thermonuclear flashes in the surface layers of an accreting neutron star were first proposed by WOOSLEY and TAAM [23] and MARASCHI and CAVALIERE [24] as a model for X-ray burst sources. During the last few years, the preponderance of accumulating evidence has come to strongly favor this model; detailed calculations of such flashes have been remarkably successful in accounting for the general properties of X-ray bursts (JOSS [53]; see [6,7,8] for reviews of this and subsequent work). In this picture, a neutron star undergoes accretion from a binary stellar companion. The freshly accreted matter is rich in hydrogen and/or helium. However, at depths greater than $\sim 10^4$ [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. 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

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will proceed via thermonuclear reactions, rather than electron capture or pycnonuclear reactions (which are driven by high densities rather than high temperatures).

These burning shells are unstable to thermal runaway [8] due to the strong temperature dependence of the thermonuclear reaction rates and the partial degeneracy of the burning material. Hydrogen is fused into helium in the outermost burning shell of the neutron star. However, the reaction rate of the *p-p* chains is insufficiently temperature sensitive to produce a thermal runaway in this shell. Most of the hydrogen burning actually occurs via the CNO cycle, which is modified at the prevailing high temperatures and whose rate reaches a saturated value for temperatures in excess of $\sim 7 \times 10^7$ [K]. This saturation effect results from the appreciable lifetimes ($\sim 10^{2-3}$ [s]) of the beta-unstable seed nuclei that participate in the cycle. Thus, hydrogen-burning runaways are usually unable to release large amounts of energy on the time scale of an X-ray burst [25,26]. The next shell inward is the helium-burning shell, which should generate rapid and energetic thermonuclear flashes over a wide range of conditions. It is unlikely that there will be any other significant burning shells, as numerical calculations (see [6,7,8] for references) indicate that nearly all of the matter will usually be processed into massive nuclear species within the hydrogen- and helium-burning shells.

Numerical computations of the evolution of the surface layers of an accreting neutron star (see [8] for references) have shown that helium-burning flashes have the following properties: (i) A full $\sim 10^{21}$ [g] of matter (or even more, under some circumstances) typically accumulates on the neutron-star surface before each flash and a total energy of $\sim 10^{39}$ [ergs] is released per burst. (ii) For accretion rates comparable with those observed in X-ray pulsars ($\lesssim 10^{17}$ [g s^{-1}]), the time interval between flashes is $\sim 10^{4-5}$ [s]. (iii) Convection is important just above the burning shell, though many of the time scales are determined by the diffusion of radiation through the radiative zone. 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. The bursts of electromagnetic radiation from the neutron-star photosphere have rise times of ~ 0.1 [s], peak luminosities near the Eddington limit ($\sim 10^{38}$ [erg s^{-1}]), decay time scales of ~ 10 [s], and peak effective temperatures of $\sim 2 \times 10^7$ [K].

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The behavior of the surface luminosity L as a function of time t following a thermonuclear flash in two models calculated by AYASLI and JOSS [27] is shown in Fig. 5. The typical rise times, decay time scales, peak luminosities, total emitted energies, spectral properties, and recurrence intervals of observed type I X-ray bursts [6,7] are reproduced remarkably well by such calculations. However, there remain a number of difficulties in the interpretation of X-ray burst sources as thermonuclear flashes. In the following sections, we describe some of these problems and elaborate on perhaps the most important one of all—the "Super-Eddington Problem".

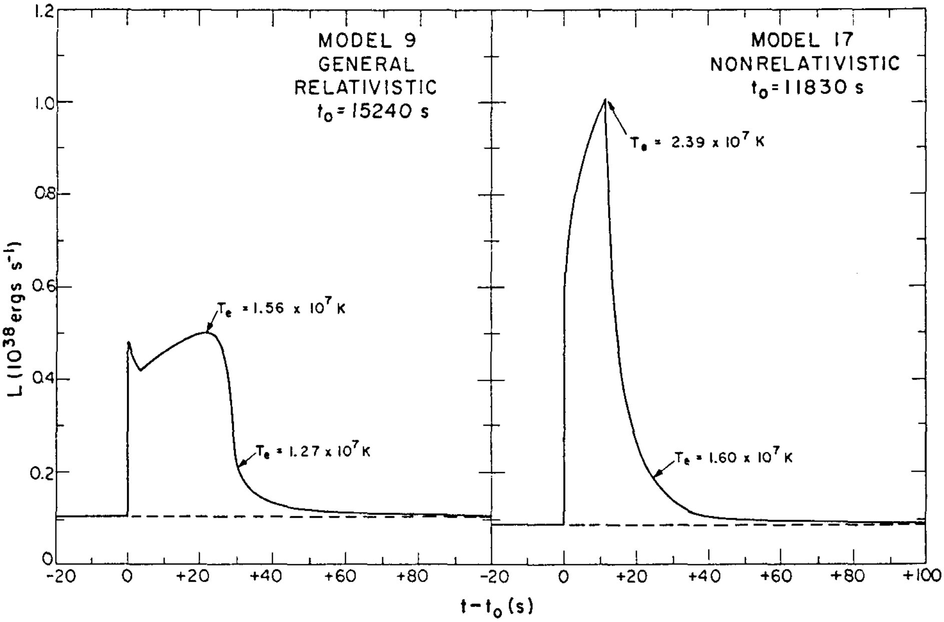

Figure 5: *Two thermonuclear flash models calculated by* AYASLI and JOSS [27]. *The neutron star is assumed to be nonrotating and unmagnetized and to have a mass of* 1.41 $M_\odot$, *a radius of* 6.57 [km], *and a core temperature (as measured by an observer on the neutron-star surface) of* 2×10^8 [K]. *The time* t_0 *is the interval from the onset of accretion (at time* $t = 0$*) to the start of the flash, the effective temperature* T_e *is indicated at a few points, and the dashed lines indicate the level of persistent accretion-driven luminosity in each case. Model 17 assumes identical parameter values to those of model 9, but all general relativistic corrections to the equations of stellar structure and evolution have been suppressed.*

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III. THEORY VS. OBSERVATIONS: DISCREPANCIES

One problem with simple versions of the thermonuclear flash model is their inability to account for the extremely short burst intervals ($\sim$ 4 to $\sim$ 10 [min]; see [6,7,8] and references therein) that have been observed in some events. In the clearest of these instances, where two bursts from the source XB1745-24 in the globular cluster Terzan 5 were separated by an interval of $\sim$ 8 [min], the associated persistent X-ray luminosity was not especially high, and the ratio α of time-averaged persistent X-ray luminosity to time-averaged burst luminosity was effectively much less than unity [28]. Thus, there was insufficient time for nuclear fuel to accumulate onto the neutron star between flashes. It is still not clear how two nearly identical bursts can be produced so close together in time. A second difficulty is that none of the numerical calculations of neutron-star thermonuclear flashes that have been carried out thus far reproduce many of the observed complexities in burst structure and recurrence patterns, which vary from one burst source to another and often vary with time in a given source [6,7,8]. Burst intervals can vary greatly (from $\sim$ 1 [hour] to $\sim$ 1 [day]) without an obvious associated change in the observed persistent X-ray flux and thus without an obvious associated change in the accretion rate. It is quite possible that many of these complexities will be better understood when further theoretical complications, such as violations of spherical symmetry, the thermal inertia of the neutron-star surface layers, the residual radioactivity of the flashed matter, and the nuclear fuel left unburned by a flash, are fully incorporated into future calculations (see [8] for references).

Perhaps the most puzzling discrepancy between theory and observation is the apparent existence of peak luminosities in some bursts that appear to exceed the Eddington limit

$$L_{\mathrm{ed}} = \frac{4\pi c G M}{\kappa_{\mathrm{T}}(1+z_{\mathrm{s}})}\,, \tag{1}$$

where κ_{T} is the Thomson scattering opacity at the neutron-star surface and $(1+z_{\mathrm{s}})^{-1}$ is a general relativistic correction factor, by factors of $\sim$ $3-10$ for neutron stars of reasonable mass. There are two parts to this problem:

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(1) The observed fluxes near the peaks of some bursts often imply super-Eddington luminosities for isotropic emission and an assumed value of the source distance. Unless the distance to a particular burst source is known independently, the calculated luminosities are highly uncertain. However, some burst sources are contained within globular clusters [29], whose distances are thought to be well calibrated, while others lie in directions strongly concentrated toward the Galactic center (see Fig. 3) and are believed to belong to a distribution that is spatially centered at the Galactic center [30,31]. For these classes of sources, the Eddington limit is exceeded in many bursts by factors of up to 10 (if one assumes isotropic emission and a distance of ~ 9 [kpc] to the Galactic center).

(2) The peak color temperatures of some bursts exceed the maximum value for neutron stars emitting blackbody radiation at or below the Eddington limit and obeying a physically reasonable mass-radius relation. This problem, however, may be a consequence of the assumption that the emitted spectrum is that of a blackbody (i.e., that the color temperature is equal to the effective temperature). Recent calculations of neutron-star atmospheres (see [32,33,54,34,35] and §IV below) suggest that the color temperature is greater than the effective temperature under the conditions prevailing in neutron-star surface layers radiating near the Eddington limit. The super-Eddington luminosities thus inferred may therefore disappear when the "true" effective temperature is known.

We shall elaborate on the theoretical issues surrounding the super-Eddington problem in the following section.

IV. THE SUPER-EDDINGTON PROBLEM

There are three fundamental theoretical problems with the supposition that the peak luminosity in an X-ray burst is very much larger than $L_{\rm ed}$ (see, e.g., [36]): (i) The total nuclear energy released in a neutron-star thermonuclear flash is smaller by a factor of ~ 10 or more than the gravitational binding energy of the flashed material [25,26]. Hence, there is insufficient energy to drive off most of the mass in the neutron-star surface layers. In fact, a large portion of the surface layers above the flashing shell quite generally remains in hydrostatic and radiative equilibrium following the flash (se, e.g., [27]). Since the radiative luminosity cannot greatly ex-

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ceed $L_{\rm ed}$ in the radiative region without resulting in implausibly high rates of mass loss, this region effectively acts as a "barrier" across which luminosities well above the Eddington limit cannot penetrate. (ii) Even if the aforementioned "barrier" could be penetrated, a radiative luminosity well in excess of $L_{\rm ed}$ would be associated with a total (radiative plus enthalpic plus kinetic energy) luminosity enormously higher than the radiative luminosity itself. However, the time-integrated radiative luminosity of a burst is not greatly smaller than the total energy available in a thermonuclear flash, as inferred from the measured accretion rates and the recurrence intervals between bursts [8]. Thus, a radiative luminosity much above the Eddington limit seems to require a total energy in the burst far in excess of the available energy. (iii) The mass loss associated with super-Eddington luminosities would cause a large increase in the photospheric radius and a concomitantly large decrease in the effective temperature of the neutron star to values well below the X-ray range.

In principle, however, dynamical effects may still be generated following a thermonuclear flash if a small fractional mass of the surface layers receives a disproportionate share of the released energy. In fact, if the luminosity remains even slightly super-Eddington for a time much longer than the dynamical time scale at the neutron-star surface ($\sim 10^{-4}$ [s]), a quasi-static wind may become established, resulting in the elevation of the photosphere to a level well above the original neutron-star surface [37,38,39,40,41,42]. Such photospheric expansion in response to flashes that involve large energy releases and concomitantly high luminosities is probably the explanation for apparent variations in the size of the X-ray-emitting regions during the course of some X-ray bursts. In such instances, the radius of the (presumably spherical) emitting surface is seen to increase from $\sim$ 10 [km] to a value several times larger near the peak of the burst, and it is then observed to decrease back to a value near 10 [km] during the burst decay (see, e.g., [10,29]). The conjecture that such events result from high radiation pressure at the neutron-star photosphere is further strengthened by the observation (see, e.g., Fig. 5 in ODA and TANAKA [28]) that radius variations are detected primarily among the most luminous bursts from a given source.

Further evidence of dynamical phenomena following a thermonuclear flash is provided by the distinct precursors observed in some of the longer

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Type I X-ray bursts (Fig. 1). These precursors consist of relatively brief but intense X-ray emission just before the start of the main burst [9]. LEWIN *et al.* [43] and TAWARA *et al.* [44] have suggested that the interval between the precursor and the main event corresponds to a sharp reduction in the color temperature of the emitted radiation, under conditions of roughly constant bolometric luminosity. The drop in color temperature presumably results from a large increase in the radius of the neutron-star photosphere during the emission of an intense, radiatively driven wind. If this picture is correct, the precursor phenomenon is an extreme example of photospheric variations due to mass loss from the neutron star; the large magnitude of the variations in photospheric radius is probably related in a way not yet understood to the large energy of the outburst.

Models for quasi-static winds from neutron stars were first considered by WALLACE *et al.* [37], and subsequently developed by EBISUZAKI *et al.* [38], KATO [39], MELIA and JOSS [40], QUINN and PACZYŃSKI [41], and JOSS and MELIA [42]. The two chief (and common) ingredients in these calculations are: (i) that the flow is quasi-static, and (ii) that the temperatures are sufficiently high for the wind acceleration to be driven primarily by Compton-scattering opacity. Although the wind models differ in some of their physical assumptions, they nonetheless agree on the basic observational character of radiatively driven winds following a thermonuclear flash in the surface layers of a neutron star (see Fig. 6). The calculations show that most of the energy flux in excess of the Eddington limit at the base of the wind is converted efficiently into the gravitational potential energy flux of the outflowing matter. In fact, the radiative plus mechanical energy flux at infinity is never more than $\sim 10\%$ greater than $L_{\rm ed}$. Moreover, the wind models predict very large photospheric radii and concomitantly low effective temperatures, well below the X-ray range, for even modest mass-loss rates. Such models may thus indeed provide the explanation for the observational phenomena described in the preceding two paragraphs. However, they also reaffirm the conjecture that the flashing surface layers of a neutron star cannot radiate a luminosity substantially in excess of the Eddington limit.

In principle, the Eddington limit could be exceeded if the assumption of spherical symmetry were violated (as would be the case, for example, if

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only a portion of the neutron-star surface area participated in each flash). However, in the absence of beaming of the emitted radiation, a breakdown of spherical symmetry is unlikely to help this problem; in fact, the reduction in surface area and concomitant reduction in total burst energy would tend to lower the peak luminosities even further. It is unlikely that the suppression of radiative opacities by a magnetic field [45] will solve this problem, since magnetic fields that are sufficiently strong ($\gtrsim 10^{12}$ [G]) to reduce the opacity should also funnel the accretion flow onto the magnetic polar caps of the neutron star, thereby suppressing thermonuclear flashes at moderate accretion rates [45]. Special relativistic effects that reduce the electron-scattering opacity at high temperatures ($\gtrsim 10^{8}$ [K]) are significant below the neutron-star surface [46,47,48], but these effects have little influence upon the opacity at the photosphere itself (or, in cases where a wind is generated, in the extended envelope above the pre-flash surface of the neutron star).

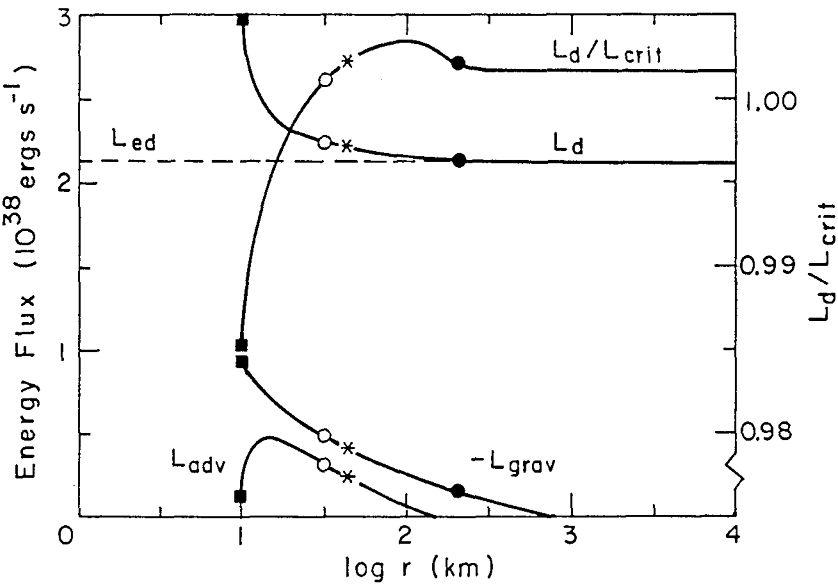

Figure 6: *A wind model with a mass loss rate of* 5×10^{17} [g/s]. *Here,* $L_{\rm ed}$ *is the Eddington luminosity,* $L_{\rm d}$ *is the radiative luminosity diffusing through the gas,* $L_{\rm adv}$ *is the radiative luminosity advected with the wind, and* $L_{\rm crit} = (\kappa/\kappa_{\rm T})L_{\rm ed}$ *is the (local) critical luminosity, which is less than* $L_{\rm ed}$ *because of relativistic corrections to the opacity at high gas temperatures. The characteristic radii in the wind are: the sonic point (○), the thermalization point (*), and the scattering phototsphere (●). This figure is from* JOSS and MELIA [42].

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Given the strength of the above arguments, the more recent efforts to solve the super-Eddington problem assume *ab initio* that the radiative luminosity from bursting neutron stars is never more than a few percent above the (locally determined) Eddington limit. In the scenario proposed by VAN PARADIJS and STOLLMAN [49], a relativistic wind following the thermonuclear flash Doppler shifts the X-rays and produces a luminosity which is super-Eddington in our frame of reference but below the Eddington limit when measured in a frame comoving with the wind. However, the existing models of neutron-star winds [37,38,39,40,41,42] seem to preclude the high flow velocities needed in this picture. MELIA and JOSS [36] have suggested a wind-disk interaction model in which a wind carrying a kinetic energy flux of at least $\sim$ 30 times the Eddington limit plows into the surrounding accretion disk. A bow shock forms if the wind is supersonic, and the resultant heating of the wind material can enhance the X-ray luminosity of the source. The observational characteristics predicted by this model are consistent with the observed properties of type I X-ray bursts, but it is unclear whether such strong winds can actually be generated following a thermonuclear flash. Preliminary calculations by MELIA [50] indicate that the wind-disk interaction model may also be viable in the "weak wind" limit if the disk is geometrically thick, so that the region of the disk close to the stellar surface can collimate the wind and thereby beam the radiative flux. It remains to be seen, however, if the disk structure can indeed provide the necessary collimation of the wind. Arguing that none of these scenarios is convincing, EBISUZAKI *et al.* [38] propose to eliminate the super-Eddington problem by suggesting that the average distance to the burst sources (and hence the distance to the Galactic center) is near $\sim$ 5 [kpc] rather than the generally accepted value of $\sim$ 9 [kpc]. It seems highly questionable, however, that the Galactic center could be that close.

Over the past few years, substantial progress has also been made on the theory of radiative transfer in neutron-star atmospheres and its relevance to the super-Eddington problem [32,33,54,34,35,51]. The interpretation of the inferred color temperature, T_c, as equivalent to the effective temperature, T_e, is suspect, because both Compton scattering and the frequency redistribution by nongrey opacities during a flash in

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the neutron-star atmosphere lead to a hardening of the emitted spectrum relative to a blackbody radiating at the same effective temperature. Indeed, for the well-known case of coherent (Thomson) scattering, the ratio T_c/T_e can be increased to an arbitrarily large value (see [35] and references therein). However, since the electron recoil effect is significant at gas temperatures in excess of $\sim 1-2$ [keV], the value of this ratio is limited by the partial thermalization of the high-energy photons due to Comptonization. It is not obvious whether Comptonization softens the high-frequency branch of the emitted spectrum to the point where the spectrum is not appreciably harder than one characterized by the effective temperature. A number of authors have addressed this issue [54,34,35,51]; although the calculated spectra are somewhat dependent on the choice of absorptive opacity because of its important effect on the frequency redistribution of the radiation, it seems that a satisfactory theoretical explanation for the high observed values of T_c may be in hand.

V. CONCLUDING REMARKS

The results of both dimensional analyses and detailed numerical calculations (see §II) provide compelling evidence that the bursts from most cosmic X-ray burst sources result from neutron-star thermonuclear flashes. Moreover, the observed properties of X-ray bursts are capable, at least in principle, of placing important constraints upon the fundamental properties of the underlying neutron stars, especially when general-relativistic effects are taken into account. However, as documented in §§III and IV, there remain substantial problems in the interpretation of various observational features of X-ray bursts in terms of neutron-star thermonuclear flashes. In this review, we have concentrated on the "super-Eddington" problem and we have summarized recent work in this area. Although substantial progress has been made in the past few years, the full utility of the X-ray burst phenomenon as a tool for understanding the physics and astrophysics of neutron stars must await further theoretical developments.

This work was supported in part by the National Science Foundation under grant AST-8419834 and by the National Aeronautics and Space Administration under grants NSG-7643 and NGL-22-009-638.

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DISCUSSION FOLLOWING MELIA

Ebisuzaki: Temperature problem is perfectly solved by our calculation. Observed spectra are consistent with our calculated spectra.

Melia: Your results certainly look promising. However, it is my understanding that your calculation is strongly dependent on frequency redistribution by the absorptive opacity, since Comptonization alone will not harden the spectrum significantly. If that's the case, then in order to achieve the thermalization condition, you must begin the spectrum evolution rather deep in the atmosphere where the gas temperature is much higher than your assumed effective temperature. It is not yet clear to me that your use of the Kompaneets equation is then valid, since $h\nu/mc^2$ under those conditions is not always much less than 1, and the cumu-

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lative effect can be significant because of the typically large number of scatterings that are involved.

Ebisuzaki: In Madej calculation, T_c/T_e is also 1.5. Does this factor solve temperature problem too?

Melia: The calculations by Madej and Joss also show that T_c/T_e can be as high as ~ 1.5, but in their case, the spectrum is noticeably different from a Planckian shape when this ratio is $\gtrsim 1.2$. Again it is not clear whether these results solve the temperature problem because (as you'll recall from Fig. 2) the observed spectra can be fitted very well by blackbody emission.

Stein: If there is an instability, such as the formation of photon bubbles, would that solve the super-Eddington problem?

Melia: To my knowledge, no one has produced hard calculations to show that such an instability is indeed a viable explanation. Perhaps Roger Blandford could shed more light on that.

Blandford: Yes, I agree with your statement. On a different matter, what supports your hypothesized thick accretion disk? It presumably cannot be radiation pressure as this would give a steady flux of the Eddington limit.

Melia: I haven't yet thought about the details concerning the structure of the accretion flow. What I've shown is that if the disk is geometrically thick, then for plausible conditions at the neutron-star surface such a disk will collimate an optically-thick wind and produce super-Eddington fluxes along the beam direction.

Icke: Concerning your suggestion of a collimated wind: Seung-Urn Choe and I have calculated that an evaporating disk can also collimate the wind from a star. The sharpness of the collimation depends on the inner disk radius and the stellar luminosity, because the dynamic pressure of the evaporating flow confines the wind. So maybe the thick disk you want to have can exist as a transient structure.

Melia: That's an interesting suggestion and it's definitely worth looking into.

Blandford: What is wrong with your suggestion that a super-Eddington kinetic energy flux be thermalized at large distances? This would require a super-Eddington energy flux in the sub-surface layers perhaps carried by convection.

Melia: A wind-disk interaction of this kind requires very strong winds. Even if the sub-surface layers carried a super-Eddington flux, the question is then how does this (presumably) convective flux get converted into the kinetic energy flux of the wind? Unless there is a very strong variation of the opacity above the convective zone, this super-Eddington flux cannot be transported through a radiative zone which remains in hydrostatic equilibrium because of its large gravitational binding energy.

Wallace: (i) Two new estimates of the distance to the galgactic center were presented at the Charlottesville AAS meeting a few weeks ago. Both gave about 9.2 [kpc]. (ii) Some calculations of X-Ray bursts produce events lasting several hours, and are highly super-Eddington at the base

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of the photosphere (low accretion-rate models). The limitation on the energy of a neutron-star wind thus must be the speed of transfer into kinetic energy, rather than the total thermonuclear energy available. (iii) The effect of the high velocity of wind particles scattering photons from the neutron star surface may not be negligible. Spectra calculations that include this motion should be explored.

Melia: (i) If that's the case, then making the Galactic distance scale shorter to solve the super-Eddington problem is even less attractive. (ii) Yes, and that's a severe limitation because there is no obvious means of effecting such a transfer above the convective zone. (iii) I agree.

Blandford: Have you thought about using a limb-brightened atmosphere to make a modest increase over and above the Eddington limit? [If, for example, we are looking along the polar direction, the observed radiation will come preferentially from the equator and the flux on the neutron-star surface can be less than $L/4\pi D^2$.]

Melia: No, I haven't thought about that yet, but it's an intriguing possibility. Up until now, all detailed calculations of thermonuclear flashes on the surface of a neutron star have assumed spherical symmetry. However, if the accretion is mediated by a disk, it is possible that a limb-brightened atmosphere such as you describe will result from the influence of the inner edge of the disk (which perhaps extends down to the surface of the star) on the evolution of the flash.

Kalkofen: The emitted spectrum has a scattering atmosphere which appears harder than that of a blackbody. The proper treatment of radiative transfer will therefore modify the predicted spectrum in the direction of the observed one.

Melia: Scattering will indeed modify the spectrum, but you have to remember that in this energy range ($\sim$ 1 to 3 [keV]), the electron recoil effect is significant so that Compton scattering can partially thermalize the radiation. As a result, the high energy branch of the spectrum steepens and there's a limit to how much the spectrum as a whole can be hardened by scattering alone.

Fisher: This is a question jointly for the speaker and for Richard Klein: Richard Klein and Jon Arons have been treating the comptonization of X-ray photons by using a chemical potential in describing the photon distribution. How do you think the inclusion of this might affect the spectra that were calculated in this talk?

Klein: Probably not very much since these atmospheres have a Compton y-parameter greater than one, and so any fine detail in the photon distribution would tend to get washed out.

Klein: Could you comment on the difference in the Monte Carlo Comptonization calculations of London, Howard, and Taam (1984) with those of Madej and Joss (1985)?

Melia: It's hard to judge because many of the details in the calculation of London, Howard, and Taam haven't been published yet. However, I know that in their case the ratio T_c/T_e was also $\lesssim 1.6$, but it's not clear how much their evolved spectra deviate from a blackbody shape at the larger values of T_c/T_e. London, Howard, and Taam also used a more

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specific form for the absorptive opacity, which may or may not have a bearing on the result. In addition, Madej and Joss have done an exact (numerical) radiative transfer calculation, using the Feautrier algorithm.

Nordlund: This comment should perhaps wait until after the talk on γ-ray bursts, but: Could you be on the totally wrong track with the thermonuclear flash model. For example, could it be that models for γ-ray bursters (e.g., neutron-star analogues of solar flares) could be relevant for X-ray bursters also?

Melia: Probably the most telling observational characteristic in support of the thermonuclear flash model is that α (the ratio of time-averaged energy in the persistent flux to that emitted in bursts) is $\sim 10^2$, which is just right for thermonuclear flashes. It's hard to see how any alternative model could come close to accounting for X-ray burst properties such as this. For example, early in the history of X-ray bursts it was believed by some that the collapsed object in these systems was a black hole. But such a picture lost its appeal when no one could reproduce such things as the burst rise-time and decay; moreover, there is now evidence that the mass of the collapsed object is $\lesssim 2\ M_\odot$, which is more in line with the mass of a neutron star. As for the comparison between γ-ray and X-ray bursts, the characteristics of the former are distinctly different from those of the latter. For one thing, γ-ray bursts have much higher spectral temperatures, and the spectra themselves are not blackbodies. X-ray bursts, on the other hand, can be fitted very well by blackbody emission. And then there's the spectral cooling seen during the decay of X-ray bursts, and the much shorter timescale of the γ-ray bursts. I'm sure we'll hear more about this in the following talk, but I think you'll see that models for γ-ray bursts probably don't have much relevance to the X-ray burst phenomenon.

Shull: Is the model's General Relativistic formalism confined to the radiation $(1 + z)$ and gravity? Perhaps one should include GR in the radiation transport (more than redshifting along solely radial trajectories).

Melia: The most up-to-date models do employ the general relativistic equations of stellar structure and evolution and include the gravitational redshift corrections to the total luminosity. As far as I know, no one has yet carried out a calculation that includes GR in the radiative transfer. There are probably two reasons for this: (i) the problem is not easily tractable, and (ii) we're talking about a redshift correction factor of only about 1.3 on the surface of the neutron star. Incorporating a more realistic treatment of radiative transfer may thus not have a significant effect.

Nordlund: You concentrated mostly on the temperature/luminosity problem. Could you comment on (i) how severe the problem of "recharging" the burst is (short inter-burst intervals)? and (ii) how severe the problem with the poor correlation between burst-interval and burst-strength is?

Melia: These are both still fairly serious problems. The feeling is that many of the complexities will be better understood when further calculations include such things as violation of spherical symmetry, the thermal inertia of the neutron-star surface layers, and the residual nuclear

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fuel left unburned by a flash. But that remains to be seen.

Pethick: In your discussion of temperatures you stressed the importance of general relativity. Probably the mass-radius relationship for neutron stars is just as important. Would you comment on what sort of mass-radius relationship is needed to account for the data?

Melia: If the emitted spectrum is indeed that of a blackbody, and if the peak burst luminosity is less than the Eddington limit, then a color temperature of about 2×10^7 [K] is just marginally consistent with neutron-star models based on the softest physically plausible equations of state. But many bursts have peak spectral temperatures of about 3×10^7 [K]. To obtain such temperatures, we would need to have objects with $M \lesssim 0.3\ M_\odot$ and $R \lesssim 2$ [km], which are inconsistent with current models of neutron stars.

Epstein: If the color temperature exceeds the effective temperature, is the discrepancy with the neutron star M vs R relation changed?

Melia: Yes, because what's important in determining M/R is not T_c, but T_e. Thus, if $T_c/T_e \approx 1.5$ and $T_c \approx 3 \times 10^7$ [K], then $T_e \approx 2 \times 10^7$ [K], which implies $M \lesssim 1.4\ M_\odot$ and $R \lesssim 7$ [km].

Meyer: I would like to make a comment on a possible solution for these super-Eddington luminosities. The basic problem is that one would have to transport such luminosities through a layer above the thermonuclear production region which is a radiative zone. This cannot be done with radiation. One therefore has to look at a non-radiative mode of transport for these energy fluxes. I think an obvious candidate is the magnetic field (which might even be dynamo-powered in the convective hot layers) which could rather naturally transfer super-Eddington fluxes above the photosphere and dissipate their energy above it (like solar flare magnetic fields transfer subphotospheric convective energy into the thin corona and dissipate it there). There seems to be no basic difficulty of such a model with the observations that you described to us.

Melia: I'm not qualified to 'comment' on your comment, but that seems to me to be an exciting possibility.