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Thermonuclear Flashes on Accreting Neutron Stars

Our understanding of the character of nuclear processes on accreting neutron stars has had a rather tortuous development. When x-ray pulsars were discovered in 1972,[1-3] it was immediately recognized that these objects were probably neutron stars which were undergoing accretion from binary stellar companions. The following year, Rosenbluth *et al.*[4] 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. However, it was not until 1975 that Hansen and Van Horn[5] demonstrated that, under a wide variety of conditions, the nuclear burning ought to be unstable and should lead to thermonuclear flashes.

Hansen and Van Horn[5] 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 nuclear 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[6] 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 of 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.

In September 1975, x-ray bursts from the globular cluster NGC 6624 were discovered by Grindlay and Heise.[7] During the subsequent three years, ~ 30 burst sources have been discovered in our galaxy. (See Lewin[8] and Lewin and Joss[9] for reviews.) A typical x-ray burst has a rise time of $\lesssim 1$ s, a peak luminosity of $\sim 10^{38}$ erg s^{-1}, a decay time scale of ~ 10 s, and a total radiant energy of $\sim 10^{39}$ erg. Bursts from a given source recur at intervals of $\sim 10^4 - 10^5$ s; the

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recurrence intervals can be regular or erratic, and a source can have "inactive" phases when the bursts disappear for weeks or longer. (The behavior of the "rapid burster" MXB1730-335 is unique and will be discussed below.)

A number of possible explanations for the x-ray-burst phenomenon were soon advanced. (See Lewin and Joss[9] and Lamb and Lamb[10] for reviews and references.) Among the early proposals was the suggestion by Woosley and Taam[11] and Maraschi and Cavaliere[12] that x-ray bursts result from thermonuclear flashes on accreting neutron stars. This suggestion spurred more detailed investigations by Joss,[13] Lamb and Lamb[14] and Taam and Picklum[15] into the physics of nuclear flashes on accreting neutron stars and their possible relation to x-ray bursts and other phenomena. Most recently, Joss[16] and Joss and Li[22] have presented the results of detailed numerical computations of flashes of this type. In this Comment, I shall describe the results of these investigations and remark upon the rich possibilities for future developments in this field.

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 helium. However, at depths $\gtrsim 10^4$ cm beneath the surface of the neutron star, the density is sufficiently high for nuclear statistical equilibrium to 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 addition of new 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 for the burning to proceed via thermonuclear reactions rather than electron capture of 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 1.

It was first realized by Hansen and Van Horn[5] that these burning shells will tend to be unstable to thermal runaway. This instability – known as the "thin-shell instability" – was first discovered in a different context by Schwarzschild and Härm.[17] The existence and strength of the instability is 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.

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, if not completely, quenched by the saturation of the

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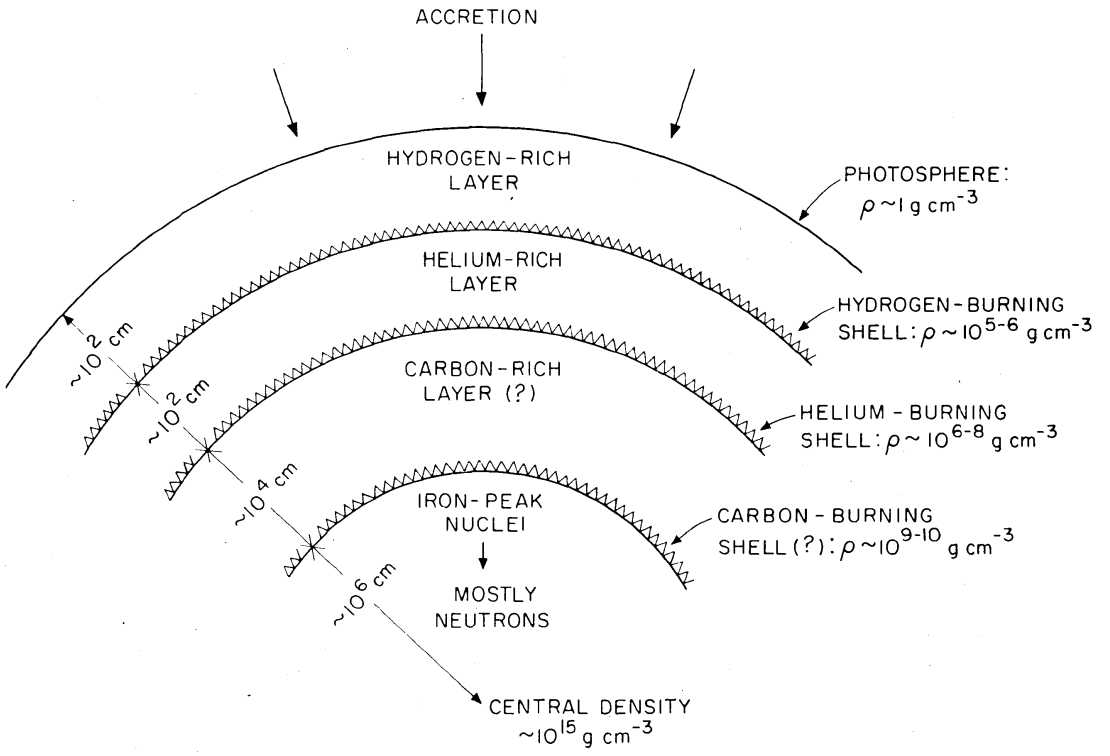


FIGURE 1 Schematic sketch of the surface layers of an accreting neutron star.

CNO cycle at very high reaction rates.[13,14] The saturation results from the appreciable lifetimes ($\sim 10^{2-3}$ s) of the β-unstable nuclei N^{13}, O^{14}, O^{15} and F^{17} that participate in the cycle. The next shell inward is the helium-burning shell, which should be unstable under 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.[15,16] However, if a carbon shell exists, it is very likely to be unstable also.[11,15]

Dimensional analysis[13,14] 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 $\lesssim 10^{39}$ erg 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 would 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 $\sim 10^{38}$ erg s^{-1}, decay-time scales of ~ 10 s, and peak black-body temperatures of $\sim 3 \times 10^7$ K (if a full 10^{39} erg of energy is indeed released in a single flash).

Carbon-burning flashes, if they exist, would involve a thicker layer of nuclear fuel and result in the release of substantially more energy. A carbon shell would be buried much deeper beneath the neutron-star surface ($\sim 10^4$ cm, compared to $\sim 10^2$ cm for the helium shell), so that the time scales for surface-luminosity

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variations resulting from a carbon flash should be much longer than those for a helium flash.[13]

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, the first detailed numerical computations of the evolution of the surface layers of an accreting neutron star have recently been carried out.

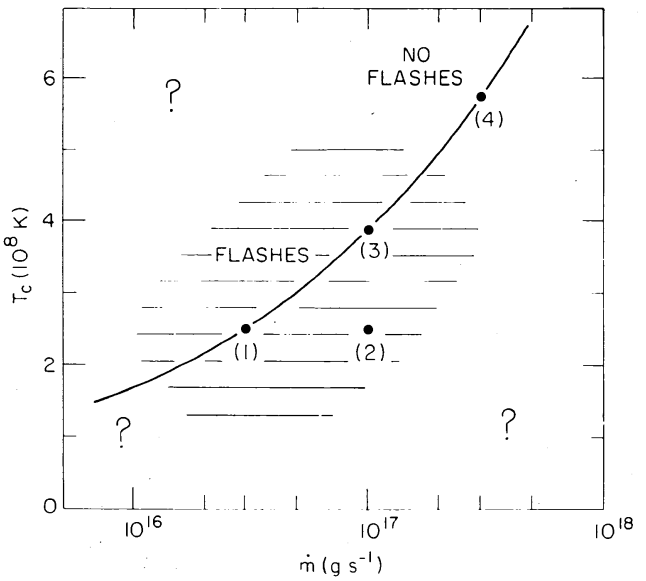


FIGURE 2 Mass accretion rates ($\dot{m}$) and core temperatures (T_c) for the evolutionary models of the helium-burning shell by Joss.[16] Points (1)-(4) denote the parameter values used in four models. All models assumed a neutron-star mass of $1.4M_\odot$ a radius of 6.6 km and no magnetic field. The solid curve passing through models (1), (3) and (4) is the estimated locus of parameter values for which the core of the neutron star is in thermal equilibrium (i.e., the heat input to the core from the surface layers during thermonuclear flashes is just balanced by the heat lost from the core between flashes[14,16]). Models (1)-(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.[16] 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}).[14] 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). A strong neutron-star magnetic field ($\gtrsim 10^{12}$ G) and the thermal effects of an outermost hydrogen-burning shell should both tend to suppress the region of flashing behavior to somewhat smaller values of $\dot{m}$ and T_c than indicated by these models (see text).[16]

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Joss[16] has explored the evolution of the helium-burning shell. His calculations made use of a number of simplifying approximations, whose importance I shall discuss in my concluding remarks. After the choice of a particular mass and radius for the neutron star, the 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 2. If the core of the neutron star is in thermal equilibrium, then the values of $\dot{m}$ and T_c are related (see Figure 2).

Three of the four models displayed thermonuclear flashes in the helium-burning shell (see Figures 2 and 3). The properties of these flashes were in good agreement with those expected from dimensional analysis.[14,13] 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 electromagnetic radiation, rather than carried inward to heat the interior of the neutron star. These properties of the flashes had not been discerned prior to the performance of detailed evolutionary computations, because they depend upon the highly nonlinear characteristics of the flash growth and decay.

Joss and Li[22] have extended these calculations to cover a range of possible neutron-star masses and radii. They found that, although various detailed features of the helium-burning flashes depend rather sensitively upon the assumed mass and radius, the basic properties of the flashes described above persist over a wide range of these parameters.

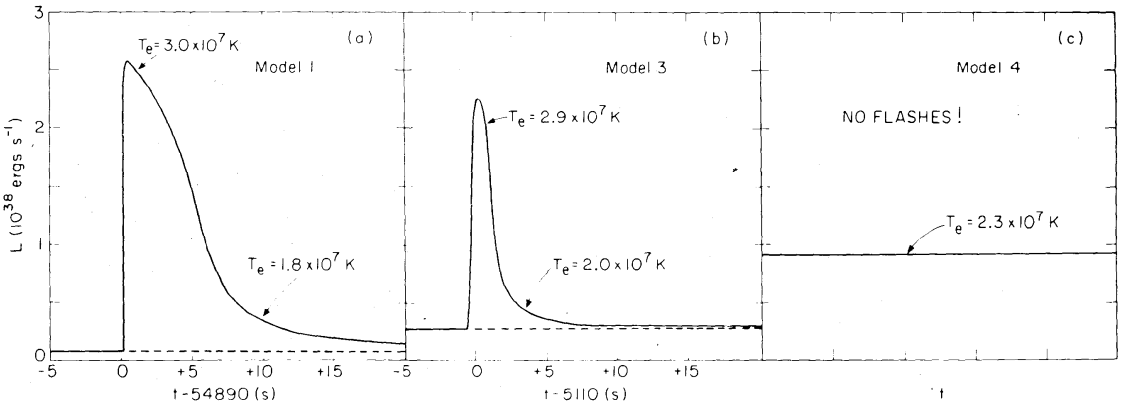


FIGURE 3 (a) The behavior of the surface luminosity L during a thermonuclear flash in model (1) by Joss[16] (see Figure 2); (b) the same for model (3). In each case, time $t = 0$ is at the start of accretion onto the neutron-star surface, the dashed line denotes the level of persistent accretion-driven luminosity and the effective black-body 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.[8,9] (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 rate of nuclear-energy generation is roughly constant and never produces more than a small perturbation on the accretion-driven luminosity.

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Taam and Picklum[15] have studied the thermal evolution of a carbon-burning shell in an accreting neutron star but have not yet carried their computations through a complete thermal flash. Their models assume low core temperatures for the neutron star ($\lesssim 10^7$ K); such cores would not be in thermal equilibrium with the surface nuclear-burning shells, but they might represent the properties of an older neutron star that has begun to accrete matter during the past $\sim 10^3$ yr

Relation to X-ray Bursts

The results of the numerical calculations of helium-burning flashes (Figure 3) 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, peak luminosities, effective black-body temperatures, decay properties, total emitted energies and recurrence intervals[8,9] are reproduced remarkably well by such flashes.

However, there are some difficulties with this model. It does not predict 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; I shall return to this point in my concluding remarks.

Another embarrassment for the helium-flash model is the ratio 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. The numerical value of α should thus be

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

where M and R are the neutron-star mass and radius, respectively.[13,14] However, some burst sources have reported[8] values of α significantly less than 1×10^2; the worst case is MXB1659-29, which was observed to have an *upper limit* of $\alpha < 25$ during one of its burst-active states.[9] 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.

If the helium-flash model is correct, the smaller values of α might simply be telling us that some nuclear-flashing neutron stars have masses moderately lower than $M_\odot$ and radii moderately larger than 10 km. (However, this explanation seems to fail for MXB1659-29, which appears to have the smallest effective

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radius among the well-observed sources.[18]) Alternatively, it is possible that the accretion-driven luminosity is emitted anisotropically and/or largely shifted to photon energies $\lesssim 1$ keV; Milgrom[19] has proposed a specific mechanism that could produce both these effects and thereby reduce the observed values of α by up to a factor of ~ 2. It has also been suggested[14] that the observed values of α might be reduced by the storage of nuclear fuel during burst-inactive phases; this idea is now rendered less likely by the results of the evolutionary computations, which indicate that each flash is sufficiently strong to consume virtually all the available fuel.

It is important to realize that 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 is $\sim 10^{1-2}$ s, and $\alpha \lesssim 2$ for this source.[20] Hoffman, Marshall and Lewin[21] have described these bursts as "type II" and the bursts 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 made the interesting speculation that the type-I bursts from MXB1730-335 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.

Relation to Other Phenomena

Let us accept, for the sake of argument, that most observed x-ray-burst sources can be understood as helium-burning flashes on accreting neutron stars. 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) that funnels the accretion onto the magnetic polar caps of an x-ray pulsar will also enhance the electron thermal conductivity in its nuclear burning shells. Moreover, the heat released by accretion and hydrogen burning 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 strongly tend to stabilize the nuclear burning shells of an x-ray pulsar against thermonuclear flashes.[15,16] Joss and Li[22] have computed evolutionary models of the helium-burning shell in the presence of an intense magnetic field; their results confirm the assertion that such fields increase the stability of the shell.

With this picture, we can also understand why the persistent x-ray flux from x-ray-burst sources is unpulsed: when the neutron-star magnetic field is sufficiently weak to allow bursting behavior, it may also be too weak to funnel the

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accreting matter.[16,23] If the magnetic field was originally as strong as in an x-ray pulsar but has since decayed, then the neutron star must be quite old ($\gg 10^7$ yr).[24] The lack of x-ray eclipses in burst sources may also reflect membership in relatively old binary systems,[25] or it may result from x-ray-beaming efefcts that set in after the neutron-star magnetic field has decayed.[19] The concentration of x-ray-burst sources in the direction of the galactic center may well be another manifestation 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.

It has been speculated[11] that carbon-burning flashes on accreting neutron stars result in cosmic γ-ray bursts. This idea has now been ruled out; 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.[13] If convection does not penetrate to the photosphere, or if it is suppressed by very strong magnetic fields in the surface layers, this conclusion is only further strengthened. More generally, the short ($\lesssim 10^5$ s) recurrence intervals between x-ray bursts, together with the lack of any observed recurrence in γ-ray bursts, rules against any direct relation between these two phenomena.[9]

The recent calculations by Taam and Picklum,[15] as well as earlier work,[11,14] indicate that up to $\sim 10^{27}$ g of carbon could be stored on a neutron star prior to the ignition of a carbon flash. The available nuclear energy ($\sim 10^{45}$ erg) is then far in excess of the amount released in an x-ray burst; in fact, this energy is comparable to the amount released by the spectrally "soft" transient x-ray sources, such as A0620-00.[26] Thus carbon flashes on an accreting neutron star might be a tenable model for such sources; this suggestion is a variant on the original idea put forth by Van Horn and Hansen.[6] (See also the discussion by Matilsky *et al.*[26]) Complete evolutionary computations of carbon flashes are highly desirable for further investigation of this possibility.

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 possible applications to a range of puzzling observational phenomena.

The only evolutionary computations of neutron-star thermonuclear flashes that have been completed to date[16] relied on a number of simplifying assumptions and approximations. These included: (1) the assumption of spherically symmetric accretion; (2) the assumption that the neutron-star core is in thermal equilibrium; and (3) the neglect of all nuclear-burning shells except the helium-

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burning shell. 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.[8,9] 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.[16] 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.

The importance of thermal equilibrium of the neutron-star core has been only tentatively explored (see Figure 2).[16] If there is a change in the average accretion rate, the thermal inertia of the core is sufficient to require the lapse of $\sim 10^3$ yr for thermal equilibrium to be reestablished.[14] Thus, departures from thermal equilibrium are entirely possible, and they could have a substantial effect upon the behavior of the nuclear burning shells.

The outer hydrogen-burning shell, while almost certainly not the seat of significant thermonuclear flashes, may nevertheless play an important role in determining the behavior of the helium-burning shell. As Taam and Picklum[15] have pointed out, the decay time scales of the β-unstable nuclei in the CNO cycle limit the hydrogen-burning rate to such an extent that, under some circumstances, the hydrogen-burning shell should be forced inward until it overlaps the helium-burning shell. This effect could significantly complicate the relevant nuclear physics and influence the stability of the two interacting shells.[15] The possible role of a carbon-burning shell interior to the helium-burning shell also remains largely unexplored.

Many of these issues can be attached by numerical computations in the immediate future. Further progress, and more surprises, are bound to be forthcoming.

P.C. JOSS

Center for Space Research and Department of Physics
Massachusetts Institute of Technology

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