THE STRUCTURE AND EVOLUTION OF THORNE-ŻYTKOW OBJECTS

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Abstract. Thorne-Żytkow objects (TŻOs) are red supergiants with neutron cores. The energy source in TŻOs with low-mass envelopes ($\lesssim 8\,M_{\odot}$) is accretion onto the neutron core, while for TŻOs with massive envelopes ($\gtrsim 14\,M_{\odot}$) it is nuclear burning via the exotic rp process. TŻOs are expected to form as a result of unstable mass transfer in high-mass X-ray binaries, the direct collision of a neutron star with a massive companion after a supernova or the collision of a neutron star with a low-mass star in a globular cluster. We estimate a birth rate of massive TŻOs in the Galaxy of $\sim 2\ 10^{-4}\,\mathrm{yr}^{-1}$. Thus, for a characteristic TŻO lifetime of 10^5–10^6 yr there should be 20–200 TŻOs in the Galaxy at present. These can be distinguished from ordinary red supergiants because of anomalously high surface abundances of lithium and rp-process elements, produced in the TŻO interior. The TŻO phase ends when either the star has exhausted its rp-process seed elements or the envelope mass decreases below a critical mass ($\sim 14\,M_{\odot}$). Then nuclear burning becomes inefficient and a neutrino runaway ensues, leading to the dynamical accretion of matter near the core onto the neutron star and its spin up to spin frequencies of up to ~ 100 Hz. The fate of the massive envelope is not entirely clear. If a significant fraction can be accreted onto the core, the formation of a black hole becomes likely. Part of the envelope may collapse into a massive disk which may ultimately become gravitationally unstable and lead to the formation of planets or even low-mass stars. We discuss the various possible outcomes and suggest a possible link between massive TŻOs and soft X-ray transients.

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1. Introduction

The study of stars with neutron cores has a history as long as the history of modern stellar-evolution theory. In the 1930s, Gamow (1937) and Landau (1938) speculated that the Sun might have a neutron core to solve the solar-energy problem. The modern study of stars with neutron cores starts with the work of Thorne and Żytkow (Thorne & Żytkow 1975, 1977). However, Thorne and Żytkow did not solve the problem of the nuclear energy source in massive supergiants with neutron cores, now referred to as Thorne-Żytkow objects (TŻO). This was done independently by Biehle (1991, 1994) and Cannon (1993), who showed that nuclear burning in massive TŻOs occurs via the exotic rapid proton process (rp-process).

In this review we first summarize the aspects of TŻOs that are reasonably well understood, such as their internal structure and the chemical signatures by which they may be detected observationally (Section 2). We then discuss the more uncertain aspects of their evolution, in particular their formation (Section 3) and their final fate (Section 4). In Section 5 we speculate that soft X-ray transients may be descendants of TŻOs .

2. The Structure of Thorne-Żytkow Objects

The outer appearance of a TŻO is that of a more-or-less normal red supergiant (with temperature $T_{\rm eff} \sim 3200\,$K and radius $R \sim 1400\,{\rm R}_\odot$ for a TŻO of mass $M_{\rm TZO} = 15\,{\rm M}_\odot$). TŻOs obey a simple mass-luminosity relation (Cannon 1993)

$$L \simeq (1.6\ 10^5\,{\rm L}_\odot)\left(\frac{\alpha}{1.5}\right)^2\left(\frac{M_{\rm TZO}}{15\,{\rm M}_\odot}\right)^{2/3},$$

where α is the mixing-length parameter (i.e., the ratio of the mixing length to the pressure scale height). The strong dependence of the luminosity on the mixing-length parameter already indicates that the internal structure of a TŻO must be fundamentally different from that of an ordinary red supergiant (whose luminosity is independent of α).

In general, two types of TŻOs can be distinguished, based on their central energy source. In low-mass models (with envelope masses $\lesssim 8\,{\rm M}_\odot$), the main energy source is gravitational energy, released by the Eddington-limited accretion of matter onto the central neutron core. In massive models (with envelope masses $\gtrsim 14\,{\rm M}_\odot$), gravitational energy release is relatively unimportant because of the generation of e^+- e^- pairs near the core which reduces the Eddington accretion rate by a factor of 10–100. Thus, the energy source has to be nuclear energy. However, the region near the core which is hot enough for nuclear reactions to take place contains very little mass ($\sim 10^{-11}\,M_\odot$), only sufficient to produce the required surface luminosity ($\sim 10^5\,L_\odot$) for a few minutes. Therefore, fresh fuel has to be continually injected from the envelope, which in effect serves as a fuel reservoir. This implies that the burning region has to be linked with the envelope by convection, i.e., the burning zone has to be at the base of the convective supergiant envelope. This is the reason why the TŻO luminosity depends on the mixing length. A further complication is that the convective turnover time in the burning region is only ~ 0.01 s, much shorter than the β^+-decay times of many weak interactions in the CNO-Ne cycle, which have lifetimes of up to ~ 100 s. As a result, the CNO-Ne reaction chain gets hung up (by the time the β^+-decays have occurred, the matter has moved out of the hot burning region) and cannot provide the necessary energy to support a TŻO envelope.

The problem of the missing energy source has recently been solved by Biehle (1991) and, in most detail, by Cannon (1993). They showed that the energy is provided by the rapid proton process (rp-process). The rp-process (strictly speaking the irp-process, which stands for interrupted rp-process; see Cannon 1993) consists of sequences of proton-capture reactions, which are terminated when the time scale for the next proton capture exceeds the β^+-decay time; a typical reaction chain is:

$$^{23}\mathrm{Na}\,(p,\gamma)\,^{24}\mathrm{Mg}\,(p,\gamma)\,^{25}\mathrm{Al}\,(p,\gamma)\,^{26}\mathrm{Si}\,(\beta^+\nu)\,^{26}\mathrm{Al}.$$

Note that, in many respects, the rp-process is analogous to the rapid-neutron process or r-process for neutron captures.

The fact that TŻOs generate their luminosities by the exotic rp-process has two important implications. One, it is possible that TŻOs provide the main site for the generation of proton-rich elements, for which no site has been unambiguously identified in the past (Cannon 1993). Two, the rp-process provides an opportunity for distinguishing TŻOs from ordinary red supergiants. Biehle (1994) estimates that the surface abundance of many rp-process elements should be enhanced by several orders of magnitude (relative to solar) in TŻOs (e.g. Mo, Br, Rb, Y, Nb) and suggests several spectral lines of these elements which should be detectable with modern spectrographs.

In addition to the rp-process, TŻOs provide an ideal environment for the production of ^{7}Li by the ^{7}Be transport mechanism (Cameron 1955). In ordinary hydrogen burning stars, ^{7}Li is continually produced as part of the PPII reaction chain (see, e.g., Clayton 1968) by the reactions

$$^3\mathrm{He} + {}^4\mathrm{He} \longrightarrow {}^7\mathrm{Be} + \gamma \qquad (1)$$

$$^7\mathrm{Be} + \mathrm{e}^- \longrightarrow {}^7\mathrm{Li} + \nu, \qquad (2)$$

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but is also continually being destroyed by the reaction

$$^{7}\mathrm{Li} + \mathrm{p} \longrightarrow 2\,^{4}\mathrm{He}. \tag{3}$$

The equilibrium abundance in the centers of stars is determined by the balancing of the production and the destruction rates and is generally very low. However, in lithium stars (e.g., Sackmann & Boothroyd 1992) and TŻOs a blob of material spends very little time in the hot burning region and, before ^{7}Be can capture an electron, the material has moved out of the region hot enough for the ^{7}Li-destruction reaction (Eq. 3) to occur. This is possible since reaction (2) does not involve a Coulomb barrier and therefore also occurs at much lower temperatures than reaction (3) which involves a Coulomb barrier. ^{7}Li will only be destroyed when the blob of material passes again through the burning region. Because the ^{7}Li-destruction process is so inefficient, lithium stars and TŻOs are able to build up a large ^{7}Li abundance.

To illustrate this, we have performed a nucleosynthesis calculation with a full pp-reaction network for a typical $16\,M_{\odot}$ TŻO model (Podsiadlowski, Cannon & Rees 1994; the numerical procedure and the TŻO models are described in detail in Cannon 1993). We assume a solar-type initial abundance for ^{7}Li and ^{3}He. Note that this means that we make the plausible assumption that the ^{3}He abundance has not been significantly reduced in the progenitor system. In Fig. 1 we show the time evolution of the ^{7}Li and ^{3}He surface abundances. Very rapidly, the ^{7}Li abundance reaches the value seen in V404 Cyg and V616 Mon (see Section 5), which is of order the primordial ^{7}Li abundance (e.g. Boesgaard & Steigman 1985). After $\sim 10^{5}$ yr, the ^{7}Li abundance reaches a maximum some three orders of magnitude larger than the primordial value and subsequently decreases, because ^{3}He is destroyed in the TŻO envelope on this time scale. But even after 10^{6} yr, which is the maximum expected TŻO lifetime, the ^{7}Li is still larger then the primordial value. This demonstrate that TŻOs should have anomalously high ^{7}Li abundances and this can be used as a secondary indicator for identifying TŻOs, although detection of a lithium anomaly does not provide conclusive evidence for a TŻO.

3. The Formation of Thorne-Żytkow Objects

While no TŻO has yet been identified, they have been predicted to form by a variety of mechanisms: (1) the direct disruptive collision of a low-mass main-sequence star with a neutron star in a globular cluster (e.g., Ray, Kembhavi & Antia 1987); (2) the complete coalescence of a neutron star with a massive companion following a high-mass X-ray binary phase (Taam, Bodenheimer & Ostriker 1978); and (3) the disruption of a companion star by a newly formed neutron star which received a supernova kick in the

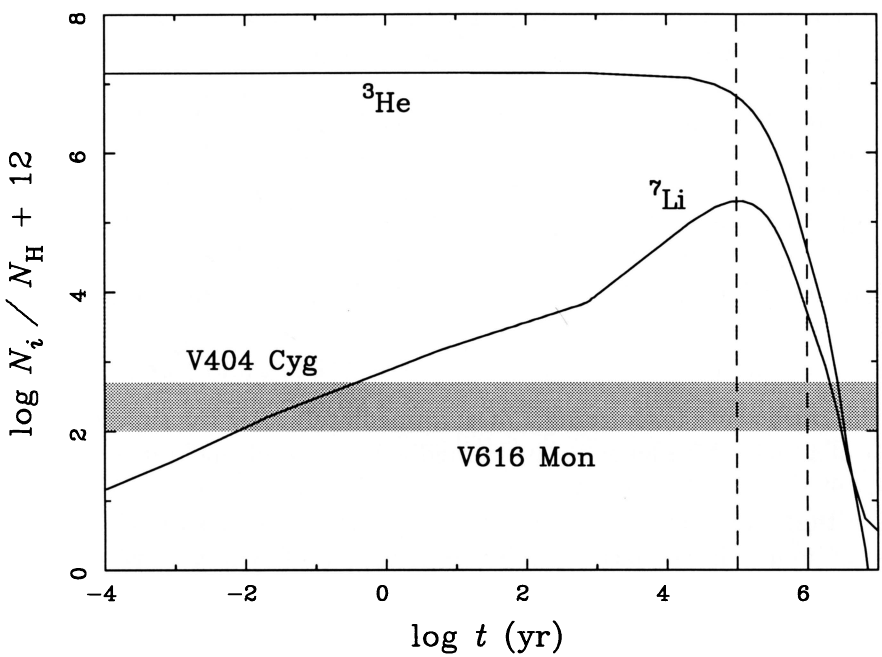

Figure 1. **The time evolution of the ^{7}Li and ^{3}He surface abundances (by number) in a typical Thorne-Żytkow object (TŻO) since its formation. The shaded area shows the range of ^{7}Li abundances measured in V404 Cyg and V616 Mon (Charles *et al.* 1994). The dashed lines indicate the range of expected TŻO lifetimes.**

direction of the companion (Leonard, Hills & Dewey 1994). In this review we will concentrate on the evolution and final fate of massive TŻOs, i.e. those formed via the second and third route.

The "classical" formation scenario for TŻOs is that they are the descendants of high-mass X-ray binaries (HMXBs) (for a detailed review of the evolution of HMXBs, see Bhattacharya & Van den Heuvel 1991). When in these systems the massive component completely fills its Roche lobe, the mass transfer rate ($\dot{M} \sim 10^{-3}$–$10^{-5}\,M_\odot\,yr^{-1}$) will exceed the Eddington accretion rate of the neutron star ($\sim 10^{-8}\,M_\odot\,yr^{-1}$) by several orders of magnitude. As a result, the neutron star will not be able to accrete most of the transferred mass, and the excess mass will form an extended envelope around the neutron star, ultimately (over)filling the neutron star's Roche lobe. The system will now have entered into a common-envelope phase, where the neutron star is completely engulfed within the massive star's envelope. Due to gas drag, the neutron star will then spiral towards the center of the system. If the orbital energy released in the process is sufficient to eject the common envelope, the end product will be a close binary, consist-

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ing of a neutron star and a helium star (i.e. the core of the massive star). If the energy is not sufficient to eject the envelope, the neutron star will settle at the center and the system will become a TŻO. Taam *et al.* (1978) estimated that TŻOs form from HMXBs with initial periods less than ~100 d. The birth rate of TŻOs, $\nu_{\rm TZO}$, can be estimated from the observed number of HMXBs with periods less than 100 d and their expected lifetimes before they fill their Roche lobes. Assuming that there are at least 10 HMXBs with the correct properties (e.g., Biehle 1994) in the Galaxy and that the HMXB phase lasts less than 10^5 yr, one obtains a *conservative* birth rate

$$\nu_{\rm TZO} \gtrsim 10^{-4}\,{\rm yr}^{-1}.$$

The third route for forming TŻOs, immediately after the supernova as a result of a kick which leads to the immediate merger of the binary (Leonard *et al.* 1994), has become significantly more important with the recent realization that supernova birth velocities of pulsars have been systematically underestimated in the past by a factor of about 3 (Lyne & Lorimer 1994). Lyne & Lorimer (1994) find an average pulsar birth velocity of $450\,{\rm km\,s^{-1}}$ with a standard deviation of $290\,{\rm km\,s^{-1}}$. A consequence of these high kick velocities is that only ~1/4 of potential HMXB progenitors survive the supernova as bound systems and that ~1/4 of those receive kicks in which the neutron star spirals into the companion star immediately after the supernova (Brandt & Podsiadlowski 1994). Assuming that the neutron star birth rate in the Galaxy is 1 every 50 yr, that ~25% of neutron stars are born in close binaries (Podsiadlowski, Joss & Hsu 1992) and that ~1/2 of the resulting systems are massive enough for rp-processing (see Cannon 1993), we estimate a TŻO birth rate for this channel of

$$\nu_{\rm TZO} \sim 10^{-4}\,{\rm yr}^{-1}.$$

Thus, both of these formation channels should be of comparable importance. This should be compared to the birth rate of low-mass X-ray binaries (LMXBs), $\nu_{\rm LMXB}$. Assuming that there are ~100 LMXBs in the Galaxy and that the lifetime of the LMXB phase is 10^7–10^8 yr, one obtains an estimate for the LMXB birth rate,

$$\nu_{\rm LMXB} \sim 10^{-6} - 10^{-5}\,{\rm yr}^{-1}.$$

Thus, the expected birth rate of TŻOs *exceeds* the birth rate of LMXBs. In other words, while TŻOs may be exotic objects, they may not be as exotic as LMXBs!

The characteristic lifetime of a TŻO is in the range of 10^5–10^6 yr (see Cannon 1993; Biehle 1994, and Section 4.1). Combining this lifetime with the above birth rates predicts that there should be between 20 and 200

TŻOs at any given time in the Galaxy. Since there are only a few thousand normal red supergiants of comparable luminosities (as estimated from Humphreys 1984), the fraction of TŻOs among the red-supergiant population should be between a few per cent up to about 10 per cent.

Chevalier (1994) has recently argued that TŻOs may not be able to form since, during the spiral-in phase, accretion onto the neutron star may occur in the neutrino-dominated rather than the Eddington-limited regime and may lead to the collapse of the neutron star into a black hole. However, his argument assumes spherically symmetric accretion at a rate determined by the orbital motion of the neutron star. This is unlikely to be a realistic assumption (Taam 1994). It appears more likely that the spiraling-in neutron star is surrounded by a quasi-hydrostatic structure (in effect, the inner envelope of a TŻO), which acts like a "hard" obstacle and deflects the large-scale flow. In addition, observationally a number of neutron stars are known which are very likely to have experienced and survived a spiral-in phase (see, e.g., Bhattacharya & Van den Heuvel 1991). Nevertheless, we note as a *caveat* that no fully realistic calculation of the formation of a TŻO has yet been performed and that it has not been demonstrated how a forming TŻO bridges the mass gap in which there are no known hydrostatic solutions (Thorne & Żytkow 1977; Cannon 1993).

4. The Fate of Thorne-Żytkow Objects

4.1. THE NEUTRINO RUNAWAY

The steady-burning phase of a massive TŻO is terminated by either of two events. One is that the supply of rp-process seed elements is exhausted and that the rp-process becomes inefficient (after $\sim 10^6$ yr). The second is that, due to the expected strong stellar wind, the envelope mass decreases below the minimum mass for nuclear burning. The minimum envelope mass is $\simeq 14\,M_\odot$, but depends strongly on the efficiency of convection (Cannon 1993). For typical red-supergiant wind mass loss rates, $\dot{M} \sim 10^{-5} M_\odot\,\mathrm{yr}^{-1}$ (Kudritzki & Reimers 1978), this will also happen after $\sim 10^6$ yr. At this point, a radiative zone develops somewhere between the burning region and the outer envelope, and the supply of fresh fuel to the burning region is choked off. (Note that there is a mass gap between low-mass models in which gravity provides the energy source and high-mass models in which the rp-process does; there are no steady-state solutions in between.) In either of these two cases, the star effectively runs out of fuel. As a result, the region just above the core will heat up until neutrino losses become the dominant energy-loss mechanism (at $\log T \gtrsim 9.4$), and accretion onto the neutron core will be no longer Eddington-limited. At this point, a neutrino runaway becomes unavoidable (see also Bisnovatyi-Kogan & Lamzin

1984). We have been able to follow the initial phase of this runaway with the code described by Cannon *et al.* (1992) and Cannon (1993). However, very quickly the evolution becomes dynamical and our calculation becomes invalid. We typically stop the calculations when the central accretion rate has reached $\sim 10^{-6}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, i.e., about two orders of magnitude larger than the "standard" Eddington accretion rate.

In the neutrino runaway, all of the material that has less specific angular momentum than the maximum specific angular momentum allowed for a neutron star will fall onto the neutron star on a dynamical time scale. We can estimate the total amount of accreted mass by assuming that the total angular momentum of the envelope is of order the initial orbital angular momentum of the progenitor HMXB and that the TŻO envelope is in solid-body rotation. The latter is likely to be a good approximation for our purposes, since convection is very efficient in redistributing angular momentum and will prevent any strong differential rotation in the envelope. For an initial HMXB with an orbital period P, consisting of a $1.4\,\mathrm{M}_\odot$ neutron star and a $15\,\mathrm{M}_\odot$ companion, the angular velocity, ω, of the resulting TŻO (with a radius $R \simeq 1400\,\mathrm{R}_\odot$ and envelope moment of inertia $I_{\mathrm{env}} \simeq 8\;10^{61}\,\mathrm{g\,cm^2}$) is

$$\omega \sim (3\;10^{-9}\,\mathrm{s}^{-1})\,P_{10\,\mathrm{d}}^{1/3},$$

where $P_{10\,\mathrm{d}} \equiv P/10\,\mathrm{d}$. This is much less than the maximum possible (break-up) angular velocity at the surface of a typical TŻO, $\omega_{\mathrm{max}} \sim 5\;10^{-8}\,\mathrm{s}^{-1}$. Thus, TŻOs are expected to be relatively slow rotators. This also implies that most of the material that is accreted onto the neutron star during the TŻO phase ($\lesssim 10^{-4}\,\mathrm{M}_\odot$ for a lifetime of 10^6 yr and a reduced Eddington accretion rate of $10^{-10}\,\mathrm{M}_\odot$) has very little specific angular momentum and that the neutron star will be spun down rather than spun up in this phase. The total mass, ΔM_{acc}, that can be accreted directly during the neutrino runaway is the mass within a cylinder of radius R_{max} given by the conservation of specific angular momentum

$$R_{\mathrm{max}}^2\,\omega \simeq \sqrt{G M_{\mathrm{NS}} R_{\mathrm{NS}}},$$

where the right-hand side gives the maximum (Newtonian) specific angular momentum of a neutron star of mass M_{NS} and radius R_{NS}. For $M_{\mathrm{NS}} = 1.4\,\mathrm{M}_\odot$ and $R_{\mathrm{NS}} = 10^6\,\mathrm{cm}$, we obtain from our TŻO models

$$\Delta M_{\mathrm{acc}} \sim (3\;10^{-2}\,\mathrm{M}_\odot)\,P_{10\,\mathrm{d}}^{-1/3}.$$

Similarly, we can estimate the total angular momentum accreted,

$$\Delta J_{\mathrm{acc}} \sim (6\;10^{47}\,\mathrm{g\,cm^2\,s^{-1}})\,P_{10\,\mathrm{d}}^{-1/3}.$$

For a typical neutron star model (with a moment of inertia $I_{\rm NS} \simeq 10^{45}\,{\rm g\,cm^2}$), a slowly rotating neutron star can thereby be spun up to a spin period

$$P_{\rm NS} \sim (10\,{\rm ms})\,P_{10\,{\rm d}}^{1/3}.$$

This period is typical of many "recycled" pulsars, but not as short as the period of the shortest millisecond pulsars.

4.2. THE ENVELOPE COLLAPSE

The fate of the large TŻO envelope is less obvious and is mainly governed by the competition of its cooling time scale and the various (uncertain) viscous time scales (Krolik 1984). After the initial neutrino runaway, the inner part of the envelope will be centrifugally supported. If the viscous time scale of the bulk of the envelope is shorter than the cooling time, it can be supported by viscous energy transport from the gravitational energy released in the inner contracting part. The initial cooling time will be of order the Kelvin-Helmholtz time of the TŻO ($t_{\rm KH} \sim 10$ - $100\,{\rm yr}$). If convection provides the dominant angular-momentum transport mechanism, the viscous time scale, $t_{\rm visc}$, will be of order the convective turnover time times the square of the number of pressure scale heights in the envelope. For the bulk of the envelope (which contains most of the mass), this time scale is only a few times longer than the dynamical time scale ($t_{\rm visc} \sim 1$ - $10\,{\rm yr}$). This is not much shorter than the Kelvin-Helmholtz time. Thus, initially the envelope can probably be supported by viscous energy dissipation. However, the mass in the inner centrifugally supported disk increases and ultimately most of the envelope is likely to form a disk-like structure with a characteristic radius $r_{\rm centr}$, (where the Keplerian specific angular momentum equals the initial specific orbital angular momentum in the outer envelope), of order, but somewhat smaller, than the initial binary separation,

$$r_{\rm centr} \sim (3\;10^{11}\,{\rm cm})\,P_{10\,{\rm d}}^{2/3}.$$

The further evolution of this massive, disk-like structure depends on when gravitational instabilities start to develop and whether these lead to bar instabilities or disk fragmentation. This also depends on the amount of material accreted by the central object, which in turn is governed by the viscous time scale of the inner envelope. As a result, a variety of different outcomes are possible.

The central object may be become either a slightly spun up neutron star or, perhaps more likely, a stellar-mass black hole. If the massive disk fragments into self-gravitating objects, these will ultimately form one or more low-mass objects. These may be planet-mass objects ("giant planets") or, in view of the large available mass in the disk, more probably, low-mass stars. Whichever the outcome, the result is bound to be of some interest.

(1) The final system may be a spun up pulsar, possibly surrounded by one or more planets. This possibility requires that the system can expel some $10\,M_\odot$, for example, by a pulsar ejection mechanism (see, e.g., Ostriker & Gunn 1971). We note that, since most of the envelope mass is at a large distance from the neutron star ($\sim 10^{14}$ cm) and hence has very low binding energy, very little mass has to be accreted onto the neutron star to generate enough energy to, in principle, eject the whole envelope. A distinctive feature of the resulting single, recycled pulsars would be that they would have relatively low space velocities, since HMXBs, unlike LMXBs, only receive a system kick velocity of $50 \pm 20\,\mathrm{km\,s^{-1}}$ as a result of the supernova in which the neutron stars formed (Brandt & Podsiadlowski 1994). Indeed, a significant fraction of such systems could remain bound in young globular clusters and possibly contribute to their neutron star (millisecond pulsar?) populations.

(2) If the pulsar is surrounded by low-mass stars (with a characteristic separation $\gtrsim r_{\mathrm{centr}}$), the system would be a potential progenitor for a low-mass X-ray binary. While only a fraction of all TŻOs would be sufficient to produce all LMXBs in the Galaxy (see Section 3), the spatial distribution of LMXBs in the Galaxy suggests that their progenitors are population I systems that received a substantial supernova kick (e.g., Bailes 1989; Naylor & Podsiadlowski 1993; Brandt & Podsiadlowski 1994). Since this is inconsistent with the distribution of HMXBs and hence TŻOs, this possibility is not favoured.

(3) The most likely outcome may be a stellar-mass black hole. The central neutron star can be converted into a black hole provided that the viscosity in the envelope can transfer angular momentum fast enough to maintain accretion in the (high $\dot{M}$) neutrino-dominated regime rather than the Eddington-limited regime after the initial neutrino runaway. Once a black hole has formed, subsequent accretion from the envelope becomes easier since photons are trapped into a flow and are accreted by the black hole (Begelman & Meier 1982). If the black hole is single or surrounded by planets, this would perhaps be the least interesting possible outcome, since it would be extremely difficult to discover such systems.

(4) If the black hole is surrounded by one or more stellar-mass objects, such systems would be excellent candidates for the progenitors of soft X-ray transients like V404 Cygni and V616 Mon (A 0620–00).

5. Soft X-Ray Transients

V404 Cyg and V616 Mon (A 0620–00) are members of a class of X-ray binaries, known as soft X-ray transients, which are widely believed to consist of a stellar-mass black hole and a low-mass companion. In V404 Cyg, the minimum mass of the compact object is $6.3\,M_{\odot}$ (Casares, Charles & Naylor 1992). In addition, Tanaka (e.g., Tanaka 1992) has argued from an observational point of view that soft X-ray transients are relatively common. This is rather puzzling since the formation of such systems in a scenario analogous to the formation of cataclysmic variables (see, e.g., Romani 1992) requires a number of assumptions, some of which may be difficult to fulfill. Most importantly such a scenario requires close binaries with an extreme initial mass ratio. This is not favoured by observations which suggest that the components of massive close binaries are typically of comparable mass (e.g., Garmany, Conti & Massey 1980). In addition, a model in which the progenitor of a soft X-ray transient experienced a common-envelope phase requires that the orbital energy released by the spiral-in of a low-mass star is sufficient to eject a very massive common envelope. This may be possible for binaries with very large initial separations, for which the common envelope would be only loosely bound, but even then only if the common-envelope ejection process is very efficient. While this may be the case, it is clear that the formation of soft X-ray transients by this route would be a very rare event, with a birth rate much lower than the already low birth rate of LMXBs (also see Romani 1992).

On the other hand, the formation of a black-hole binary with a low-mass companion may be a rather natural outcome of the evolution of a TŻO. Although a TŻO scenario involves more uncertainties than a more *conservative* common-envelope scenario, the birth rate could be quite high, even substantially higher than the birth rate of LMXBs (see Section 3).

A TŻO scenario allows several possible tests. First, one might expect that, in a significant fraction of systems, more than one companion is formed (i.e. a hierarchical multiple system). Second, such systems should have relatively low space velocities and should therefore have a very small Galactic disk scale height, as is indeed observed for soft X-ray transients (White 1994). Third and most importantly, the companion should show signatures of rp-processing and an enhanced lithium abundance (see Section 2). The latter has been seen in V404 Cyg and V616 Mon (Martin *et al.* 1992; Charles *et al.* 1994). The observed abundances are consistent with our calculations, although they seem to be somewhat too low (see Section 2 and Fig. 1), in particular if the TŻO lifetime is only a few 10^5 yr. A likely explanation for this discrepancy is that the ^{7}Li abundance has been reduced during the "main-sequence" phase of the newly formed companion stars. For G and

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K dwarfs, main-sequence ^{7}Li burning can reduce the ^{7}Li abundance by up to three orders of magnitude (for a review of lithium burning in stars, see Michaud & Charbonneau 1991).

V822 Cen (Cen X-4) is another X-ray binary in which the stellar companion has an anomalously high ^{7}Li abundance (Charles *et al.* 1994). Unlike the other two systems, the compact component is known to be neutron star since it exhibits X-ray bursts. While this may argue somewhat against a TŻO scenario as a generic explanation of lithium anomalies in these systems, we emphasize that it does not rule it out, since, as discussed in Section 4, the TŻO collapse may lead to the formation of black-hole as well as neutron star binaries. Whether the neutron star is transformed into a black hole might, for example, depend on the total angular momentum in the TŻO envelope, which in turn depends on the initial orbital period of the TŻO progenitor and/or the TŻO formation scenario (Section 3).

Fortunately, detection or non-detection of the predicted rp-process anomalies should conclusively verify or refute our suggested TŻO connection for the formation of soft X-ray transients. If it were indeed confirmed, it would provide an indirect proof of the existence of TŻO.

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