Are peculiar Wolf-Rayet Stars of type WN8
Thorne-Żytkow Objects?

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Abstract. Most population I Wolf-Rayet (WR) stars are the He-rich descendants of the most massive stars ($M_i = 25 - 100 M_\odot$). Evidence has been accumulating over the years that among all pop I WR stars, those of the relatively cool, N-rich subtype "WN8" are among the most peculiar: 1. They tend to be runaways, with large space velocity and/or avoid clusters. 2. Unlike their equally luminous WN6,7 cousins, only a very small number of WN8 stars are known to belong to a close binary with an OB companion. 3. They are the systematically most highly stochastically variable among all (single) WR stars.

Taken together, these suggest that many WN8 stars may originally have been in close binaries (like half of all stars), in which the original primary exploded as a supernova, leaving behind a very close binary containing a massive star with a neutron star/black hole companion (like Cyg X-3). When the massive remaining star evolved in turn, it engulfed and eventually swallowed the compact companion, leading to the presently puffed-up, variable WN8 star. Such stars could fall in the realm of the exotic Thorne-Żytkow objects.

1. Introduction

Thorne-Żytkow Objects (TZOs) have been proposed for the first time by Thorne and Żytkow (1977). They are stars with a degenerate neutron core which provides peculiar conditions to ensure the presence of a nuclear burning region. This supports the envelope of the star, which appears like a Red Supergiant (see e.g. Biehle 1991, 1994; Cannon et al. 1992; Cannon 1993). Their lifetime in the RSG phase is also expected to last as long as for a normal RSG (i.e. with nuclear burning right to the center of the core). Being RSGs (or appearing so), TZOs probably have strong winds.

We develop here the idea that if TZOs evolve like normal RSGs do, the most massive of them will evolve further to the WR stage, following the usually adopted scenario that RSG become WR stars because of strong mass loss by stellar wind, stripping the outer envelope (see e.g. García-Segura et al. 1996).

Among the population I Wolf-Rayet stars, those of subtype WN8 are peculiar. We present here why they are good candidates to be "evolved" TZOs, formed via a binary scenario.
This paper is organized as follows: in section 2 we give the details of two binary scenarii following which TZOs can be formed. These two scenarii provide the same paradigm to explain TZOs and objects like Cyg X-3. In section 3 we discuss how these WN8 stars are really different and how they can really come from a binary evolution scenario. In section 4 we discuss observations which could be undertaken to confirm such exotic objects. Section 5 gives our conclusions.

2. Two scenarii to form TZO

In fact three scenarii to form TZOs appear in the literature. In two of them, which are discussed below, they are the result of massive close binary evolution. The point here is that they also provide a reasonable explanation for the characteristics of WN8 stars. The third scenario is discussed by Davies, Benz & Hills (1992) and will not be repeated here; it concerns the collision of a neutron star with a massive main sequence star in a star cluster.

The two scenarii discussed below are roughly the same. TZOs can be formed in a massive close binary in which the secondary goes through a RSG phase, during which it engulfs the neutron star, arising from the normal evolution of the primary. In order to form TZOs, the orbital period of the system is crucial, as well as the masses of the two components. Terman, Taam & Hernquist (1995, hereafter TTH95) have performed hydrodynamical simulations of a neutron star entering the envelope of a more-or-less evolved RSG. Their results can be used to construct one paradigm explaining both the origin of evolved TZO and objects like Cyg X-3.

2.1. First scenario

In the first scenario, the binary system is composed of an O-star and a Wolf-Rayet star, the latter of which is the primary (i.e. the initially more massive star). At the end of its evolution, following the usually adopted scenario of a WR star (Chiosi & Maeder 1986), the primary explodes as a supernova (SN) leaving behind a newly formed neutron star (NS). The rapid SN mass-loss by the primary gives a kick velocity to the system ranging from 30 to $\sim 450$ km/s and more (De Donder, Vanbeveren, & Van Bever 1997).

Then, the system is composed of an O-star and a NS. If the secondary has an initial mass between 25 and $40 M_\odot$, the evolutionary sequence follows: O→Of→RSG→WN8→WNE→WC→SN (Crowther et al. 1995). Although the orbital period has certainly changed from what it was originally, it is certainly feasible in some cases that the period could be sufficiently short to allow common envelope evolution. During the growth of the secondary envelope towards a RSG, a gradual coalescence of the NS and the secondary occurs. The NS then spirals in to the core of the RSG, which loses is loosing a significant fraction of its envelope (see below).

2.2. Second scenario

In the second scenario, the explosion of the primary is asymmetric. The amplitude and the direction of kick place the newly formed NS into a bound orbit
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with a periastron distance smaller than the radius of the secondary (Leonard et al. 1994). This process depends obviously on the orbital period. In that case the secondary must already be a RSG (implying an initial mass ratio closer to unity, so the evolutionary timescales of both stars are comparable), to ensure a non-negligible cross section. For a detailed description of how a SN explosion affects the orbital characteristics in a close binary, see, e.g. Kalogera (1996).

To first approximation we can suppose that the spiral-in of the NS inside the envelope of the secondary follows the same evolution as in the first scenario, apart from possible differences in timescales.

2.3. The common envelope phase

The spiral-in process lasts only a few years (TTH95). Although some authors (Armitage & Livio 2000) argued that a newly formed TZO experiences dramatic neutrino-losses (which implies a collapse of the object into a BH soon after its formation), other hydrodynamical simulations (e.g. Biehle 1991) show the presence of a tiny burning region (∼40 meters!) just above the degenerate neutron core which sustains the envelope mainly via rapid-proton burning. This process stops when half of the fuel (heavy elements) is burned; the lifetime of the TZO RSG is as long as it is for a "normal" RSG (Biehle 1991).

Following the simulations of Terman et al. (1995), it seems important that the secondary be at the beginning of the RSG phase to ensure that only a fraction of its envelope is lost. In fact, this fraction depends directly on the density gradient of the RSG envelope. In the case of a "young" RSG, this gradient is steep, and a large part of the mass of the star is located close to the core. When a NS spirals inside the envelope, ∼20% of the mass of the envelope is lost (sequence 1 of TTH95). This means that the NS stays inside the RSG and does not reappear later on. We are faced with two possibilities: either this fraction is sufficient for the system to appear like a WR star, or it is not sufficient, so that the system looks like a RSG and only a stellar wind will be able to remove enough of the envelope to allow visible characteristics of a WR star to appear.

2.4. Cyg X-3: a "failed" TZO?

Cyg X-3 is a well known binary system, and a strong modulated source of X-rays. It contains a Wolf-Rayet star of subtype probably WN7 and a NS orbiting with a period of only 4.8 hours (see e.g. Cherepashchuk & Moffat 1994). Within the same paradigm, the binary evolution scenario with common envelope evolution described above can lead to the formation of such an object. (In fact, the first mention about a possible link between TZOs, WN8 stars and Cyg X-3 was proposed by Cherepashchuk & Moffat 1994).

Indeed, if the secondary was evolved, the density gradient inside the envelope would be flatter, and between 85 and 100% of the RSG envelope is lost (TTH95). In that case, the NS reappears, and the system acquires a period of only a few hours.

More generally, there exists a correlation between the initial period of the system (i.e. when the binary system is O/RSG + WR) and the possible occurrence of the common envelope evolution, leaving a TZO or a "Cyg X-3"-type object (see Fig. 1).
Figure 1. Critical period as a function of the mass of the primary (in units of $M_\odot$). Figure from TTH95. The initial period of Cyg X-3 should lie in the intermediate region.
3. Why WN8 stars?

Among the population I Wolf-Rayet stars, WN8 stars show striking peculiarities. They possess three main characteristics which differ from "normal" WR stars:

1. They have often a large space velocity and/or they avoid clusters and associations (Moffat 1989). Most of the single WN8 stars in the Galaxy show a large distance from the Galactic plane (van der Hucht 2000).

2. Only a very few known WN8 stars in the Galaxy and the Large Magellanic Cloud (LMC) belong to a massive WR+O binary (Moffat 1989; van der Hucht 2000).

3. They appear to be stochastically variable, as much as polarimetrically photometrically (Drissen et al. 1987; Marchenko et al. 1998).

In order to explain these three features with one paradigm, we propose that WN8 stars are the result of massive close binary evolution in which the primary has exploded as a SN, became a NS and spiraled in to the center of the secondary. Indeed, the kick velocity often observed (or the large distance to the clusters/associations or Galactic plane) is provided by the explosion of the primary. If the NS spirals inside the envelope of the secondary and remains within (i.e. only a fraction of the envelope of the RSG is lost), it is evident that the system will not exhibit binary characteristics (no radial velocity variations can be detected).

An important point to note here is the following: Marchenko et al. (1998) showed, based on a statistical trend, that the variability observed in WN8 stars is due to core activity. Can we then ask: Could the presence of a NS in the core (even slightly off-centered) be responsible for instabilities which affect the behaviour of the envelope and then the observational characteristics?

4. Can TZOs be observed?

How can we detect and observe TZOs? Indeed, as first proposed by Cannon (1992), the burning process is a rapid-proton chain, which produces a different set of heavy elements from what we can observe in normal stars. Usually these elements are partially brought up to the surface, via convection inside the envelope. If the burning process supporting the envelope is due to the presence of a degenerate neutron core, and is located in a tiny shell above the core, unusual heavy elements, such as Mo should be created (Biehle 1994).

But if the mass loss due to the spiral-in process is not sufficient for the secondary to look like a WN8 star, the envelope of the RSG will be large and it would be difficult to detect these peculiar heavy elements in the surface. It seems reasonable to say that the more a TZO is evolved (e.g. WN8), the smaller is the envelope (or the distance between the burning region and the surface), the easier it should be to observe signatures of a degenerate neutron-core supported burning-region.

In fact, we can argue that WR stars have very strong winds, and all photospheric information is obscured by the wind. This is true mainly for hotter
subtypes. Nevertheless WN8 stars are peculiar also because they have a slow wind velocity, and hence narrow emission lines. It could be very interesting to perform the same research of heavy elements (via echelle-spectra?) among the WN8 population, that it is being done for RSG (see Kuchner & Vakil, these proceedings).

The Galaxy has about 200 known WR stars (van der Hucht 2000), among which a quarter are WNL stars (i.e. WN9 to WN6); of these a quarter are of subtype WN8. This means that \( \sim 12 \) TZO(WN8) could exist among the observed WR population in the Galaxy. In the Large Magellanic Cloud (where detailed echelle spectroscopy could also be made) one finds 3 stars of subtype WN8 (Breysacher et al. 1999).

5. Conclusion

We have presented here the two known scenarii in which TZO s form following close binary evolution and a common envelope phase. The hydrodynamical simulations of Terman et al. (1995) dealing with the entry of the NS inside the envelope of a more-or-less evolved RSG allowed us to construct a paradigm within which WN8 stars, TZO s and objects like Cyg X-3, find an explanation. We also drew attention to the peculiarities of WN8 stars which fit well in our "model". Finally we believe that spectroscopic observations might be feasible to reveal the presence of a degenerate neutron core inside single WN8 stars, which would then confirm the existence of TZO s.

To the question: "Are peculiar Wolf-Rayet stars of type WN8 Thorne-Żytkow Objects?" we should now respond "Why not?".

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