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Strategies for detecting Thorne-Żytkow objects

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Abstract. Thorne-Żytkow objects (TŻO) are likely to have high mass loss rates, such that their optical photospheres are obscured by a dusty envelope. Indentification of massive TŻO through abundance anomalies associated with the irp process in the core is more likely to be possible by observing molecular transitions in the 4–8 μm region and at mm wavelengths than in the optical. A promising molecule is SiO, with anomalously high abundances predicted for ^{29}SiO and ^{30}SiO. An upper limit for ^{30}SiO is reported for the unusually bright galactic center SiO maser OH359.762+0.120.

Key words: stars: chemically peculiar – stars: supergiants – masers – stars: OH359.762+0.120

1. Introduction

Thorne Żytkow objects (TŻO), supergiants containing a neutron core (Thorne and Żytkow 1975,1977), are expected to be formed in noticeable numbers in the evolution of massive binaries. They can form as the outcome of the common-envelope evolution of a high-mass X-ray binary after the OB primary evolved into a giant and engulfed its companion (Taam, Bodenheimer and Ostriker, 1978). Alternatively, they may form directy during a supernova explosion in a massive binary, if the kick velocity of the forming neutron star happens to be directed such that it collides with its companion (Leonard, Hills and Dewey, 1994). In the dense cores of globular clusters, TŻO can form through collisions of single neutron stars by normal stars (Ray et al. 1987). The outward appearance of a TŻO is that of a late type supergiant. Because of their high luminosity, they should be visible throughout the Galaxy, and it is possible that several are hidden in existing samples of luminous late type stars. The chances of identifying TŻO stars depend on their expected numbers, and on the expected abundance anomalies which would allow the distinction from ordinary supergiants to be made.

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Anomalous abundance patterns are expected only for TŻO with relatively massive envelopes, $M_{env} > 4\mathrm{M}_{\odot}$ (see below). This restricts possible detection to TŻO formed by the first two processes mentioned above. The formation rate of TŻO by these processes has been estimated at about 10^{-4} yr^{-1} (Biehle 1994, Podsiadlowski 1995). The predicted luminosities depend on the envelope mass (for an empirical expression of the luminosity, obtained from stellar evolution results, see Cannon (1993). For envelope masses in the range 10-20 $\mathrm{M}_{\odot}$, the luminosity is around 10^5 $\mathrm{L}_{\odot}$. Mass loss rates observed for supergiants this bright are very large, of the order $10^{-6} - 10^{-4}\mathrm{M}_{\odot}$ yr^{-1} (e.g., Sahai & Wannier 1992, Loup et al. 1993). The precise cause of this mass loss is not certain, but is likely to involve both stellar pulsation and radiation pressure on dust (e.g. Tielens 1983, Habing et al. 1994). As long as these causes are not fully clear, one can not be sure that the same mass loss rates will apply also to TŻO. Since the known processes driving mass loss originate largely in the outer envelope, of which the structure is the same in TŻO and ordinary supergiants, we assume here that the mass loss rates of TŻO will be the same as in normal supergiants. Thus, the expected life time is probably limited primarily by mass loss, and should be of the order $10^5 - 10^6$ yr. With these numbers, there would be 10-100 TŻO in the Galaxy.
Finding TŻO among the more numerous ordinary supergiants and AGB stars will be challenging. We propose here that a successful strategy should take into account both the expected abundance anomalies and the possible high mass loss rate.

2. Abundance anomalies

At low envelope mass ($M_{env} < 14\mathrm{M}_{\odot}$, Cannon 1993), the luminosity of a TŻO derives from gravitational settling of envelope mass onto the neutron star. Nuclear burning in this case takes place in a convectively stable region around the neutron star, so that no strong anomalies in the surface abundances are expected. This changes at higher envelope mass, where the models (Thorne and Żytkow, 1977) predict that the burning zone is convective. The nuclear energy generation is dominated by the interrupted rapid proton (irp) process (Cannon 1993, Biehle 1994). The high hydrogen abundance (compared with the standard stellar environments in which heavier elements are synthesized) leads to burning of the CNO elements up to and beyond the iron peak by the addition of protons (rp-process). Because the burning volume is small (close to the neutron core) and the convective velocities high, the residence time of a CNO nucleus in the burning zone is short compared with many of the β-decay times in the reaction chain. On the one hand this predicts that intermediate nuclei in the chain are mixed throughout the envelope, leading to anomalous abundances at the surface. On the other hand, it changes the reaction process by allowing β decays between successive visits of the reacting material to the burning zone (irp-process, Biehle 1991, Cannon 1993). The short residence time also implies that the Cameron mechanism (Cameron, 1955) for producing ^{7}Li is effective. Podsiadlowski et al. (1995) predict high Li abundances in TŻO as a result of this process. The production rate of heavy elements in mass losing TŻO may be high enough to explain some of the abundances seen in the terrestrial isotopic mix (Cannon, 1993).

In addition to CNO, the irp-process also processes the heavier elements in the original mixture into rp isotopes (though this adds only little to the energy generation rate). Towards the end of its life (all CNO spent) the envelope would therefore not only be enriched in the rp products, but also depleted in the original heavy elements. The total mass in metals would then also be large, of the order 7%. In practice, however, mass loss may well reduce the envelope mass below that at which the irp-process can take place before the CNO fuel is exhausted, so that such extreme conditions are not very likely to occur. The anomalous isotopes visible at the surface are decay products of intermediate isotopes along the rp-chain. Biehle (1994) gives the most detailed list of expected isotopes, and discussed especially the observability of Rb, Sr, Y and Mo through atomic lines in the visible. His list predicts a large choice of other overabundant elements, however, such as Ge, Se, Rb, Sr, Zr, Nb, Ru, Rh, Pd, Ag and Cd. In addition, certain elements are produced in amounts similar to their original abundance, but with a different isotopic distribution. These are, in particular, silicon (^{29}Si and ^{30}Si instead of ^{28}Si) and sulfur (^{33}S and ^{34}S instead of ^{32}S). Since isotopic effects are much larger for molecular transitions than for atomic ones, this suggests observation of molecules containing Si or S. Anomalous isotopic ratios in such molecules may be easier to spot than the anomalous strength of a single atomic transition.

3. Mass loss and obscuration

Because of their strong mass loss supergiants tend to be surrounded by dusty envelopes, which in many cases completely obscure the star in the visible. For this reason, a search in the infrared or at radio wavelengths may be an attractive alternative to searches based on optical spectra, in which the atomic line transitions (even if the obscuration is not severe, and the overabundances very large) are hidden in a forest of other strong molecular and optical transitions.

Obscuration due to mass loss may be less of a problem if the mass loss is asymmetric, so that there is a reasonable chance of observing objects along a less dense line of sight. Such an asymmetric outflow has been suggested for the very luminous supergiant IRC +10420 (Jones et al. 1993). Asymmetric outflow may be particularly relevant for TŻO, which must contain a significant amount of angular momentum. In a TŻO descending from a massive X-ray binary, essentially all the orbital angular momentum of the binary gets transferred to the nascent TŻO during the spiral-in of the neutron star into its companion. For a TŻO to be formed at all, this companion must be massive enough to absorb the orbital angular momentum, instead of ejecting it with the envelope in a common envelope process. For a neutron star captured by a companion during the supernova explosion, a similar amount of angular momentum may be acquired by the companion. The resulting TŻO would have a much larger moment of inertia, due to its size, than the original star so it would rotate only slowly. Yet is conceivable that this rotation may still make the mass loss from the star asymmetric, concentrated toward the equator.

4. Detection at infrared and radio wavelengths

The predicted isotopic anomalies in silicon suggest that a good candidate for observation would be SiO. Biehle's (1994) table shows a significant amount of Si produced, mostly as ^{30}Si, (75%), some as ^{29}Si (25%), while the original ^{28}Si would be depleted by the irp-process. This contrasts with the terrestrial isotopic ratios of 92%, 5% and 3% for ^{28}Si, ^{29}Si and ^{30}Si. Thus, if an isotope ratio ^{30}Si/^{28}Si of 10% could be measured to an accuracy better than a factor 2 in a TŻO candidate, it could be identified as TŻO already when only about 1/10 of the envelope has been processed.

SiO has the advantage that its transitions have been seen in circumstellar envelopes both at mm wavelengths, and at 4μm. Maser activity of SiO is common in the circumstellar envelopes of late-type giants (e.g. Nakada et al. 1992, Izumiura et al. 1994). Maser activity of ^{29}SiO and ^{30}SiO has been seen in some supergiants (Alcolea and Bujarrabal, 1992 and references therein). The lines are much weaker and narrower than those of the ^{28}SiO masers in these objects, but no clear estimates of the isotope ratios are available, because of the difficulty of interpreting the strengths of maser lines. It is clear however, that if we assume that the excitation conditions are equal for all the isotopes there is no indication for a strong enhancement of the ^{30}Si variety.

The fundamental and first overtone vibrational transitions of SiO at 8 and 4μm have been seen in the photospheric absorption spectrum of several supergiants (Hinkle et al. 1976, Geballe et al. 1979, Tsuji et al. 1994). SiO is inferred to be the dominant absorber in the 4μm region in cool oxygen-rich giants (Rinsland and Wing, 1982). The isotope ratios in the objects studied so far were near the terrestrial values (Geballe et al. 1979, Kahane et al. 1988).

Maser activity and measurable photospheric SiO absorption may be restricted to circumstellar envelopes within some range of temperature and optical depth. These conditions would depend primarily on the mass loss rate. At very high rates, the envelope may become so thick that the photospheric SiO absorption spectrum at 4μm becomes unobservable. The fundamental at 8μm would be better in this respect since the optical depth of the dust shell would be less. On the other hand, at 8μm the thermal radiation of the dust shell would start diluting the photospheric spectrum, at high mass loss rates. Whether SiO maser activity is still operating at these high rates is not known. There are some indications that the probablity of SiO maser emission diminishes at the highest mass loss rates (Nyman et al 1993). Since the mass loss rates to be expected for TŻO are not known, except that they are likely to be high, this introduces some uncertainty in their detectability at these wavelengths. If the thickness of the circumstellar envelopes of

Fig. 1. Spectra for OH359.762+0.120 for the four SiO transitions observed with the VLA. Flux scales are approximate.

TŻO is a problem, however, detection at these wavelengths is still much more likely than at optical and near-IR frequencies. Sulfur containing molecules are an interesting target for exploration, because the irp-process produces significant amounts of ^{33}S and ^{34}S, which have terrestrial abundances of only 0.7 and 4%, respectively. H_2S, SO, SO_2, CS and SiS have been seen in the circumstellar envelopes of high mass-loss objects (Ukita and Morris 1983, for a recent review see Omont et al. 1993). Accurate sulfur isotope ratios have been already been measured in the carbon star IRC + 10216 (Kahane et al. 1988), and in many star-forming regions (Chin et al. 1995). ^{72}Ge (the most abundant terrestrial isotope) is predicted to be overabundant by a factor up to 100 over solar, and may be detectable in the form of GeO (chemically analogous to SiO). Bromine is overabundant by a factor up to 400, and might be seen substituting for chlorine (several chlorides have been seen in IRC + 10216, Cernicharo and Guélin 1987).

4.1. selection of candidate objects

As hypothesized above, TŻO may have the properties of luminous, high mass loss red giants, i.e., of OH/IR sources. Most of such stars are ordinary asymptotic giant branch stars (late stages in the evolution of medium-mass stars) and red supergiants (evolved massive stars). TŻO would be among the most massive and the most luminous of these. Observationally, it is known that OH/IR sources are long period variables of which the period (several years) is believed to increase both with mass and luminosity of the star (Hughes and Wood 1990, Vassiliades and Wood, 1993). Thus, a possible strategy is to look for TŻO among very long-period sources, but this uses the underlying assumption that TŻO are similar to other OH/IR stars in their oscillation properties. A more targeted approach would be to search for OH/IR sources in known OB associations. This would have the advantage that both masses and luminosities could be estimated with sufficient accuracy. The evolution tracks for TŻO for masses $> 10\mathrm{M}_\odot$ by Cannon et al. (1992) when compared with standard evolution tracks for massive stars (Meynet et al. 1994), show that TŻO appear in the same part of the HRD as normal red supergiants of the same mass, though they are somewhat overluminous (by about one magnitude). Luminous OH/IR sources that can be plausibly related to OB asociations would therefore be good TŻO candidates.

5. Observation of OH359.762+0.120

A first test of this hypothesis was carried out by searching for ^{30}SiO maser emission in the OH/IR star OH359.762+0.120. This object is a member of a sample of OH/IR stars in the Galactic center (Lindqvist et al. 1992). It has a fairly typical OH/IR period of 758 days (Van Langevelde et al. 1993), but IR photometry reveals a very large luminosity of $\gtrsim 3 \times 10^5$ $\mathrm{L}_\odot$, exceeding the OH/IR period – luminosity relation by a factor 100, provided this star is indeed at the Galactic center distance (Blommaert et al. 1995; Jones et al. 1994). Yet it seems unlikely that it is a foreground object, because its large angular broadening, attributed to interstellar scattering places it at the same distance as other Galactic center OH/IR stars (Van Langevelde & Diamond 1991, Van Langevelde et al. 1992). The circumstellar shell of this star is known to show ^{28}SiO maser emission, indicating that the conditions in the circumstellar shell are favorable to excite the SiO molecules into the vibrational states participating in the maser mechanism (Lindqvist et al. 1991).

Observations were carried out on April 6 1995 with the 10 dishes of the VLA[1] equipped with Q–band receivers. The VLA was in the most compact (D) configuration, atmospheric conditions were reasonably good. A setup was used in which two 6.25 MHz bands are divided in 32 line channels. This allows simultaneous observing of the $v = 1$ and $v = 2$ $J = 1 \rightarrow 0$ transitions of SiO. The first part of the 1.5 hour observing time was spent on the 'normal' ^{28}SiO line, the second (longer) part was centered on the ^{30}SiO $v = 1$ and $v = 2$ $J = 1 \rightarrow 0$ transitions. Rest frequencies of 42082.398 and 41791.797 were adopted (Lovas and Krupenie, 1974). Flux calibration was done on the standard calibrator 1331+305, but is probably uncertain

[1]The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory under cooperative agreement with the National Science Foundation.

to 30% percent at this frequency and for such short observations. Phase calibration was done every 5 minutes on SgrA*. With moderate atmospheric conditions, phase calibration at the low elevations of the Galactic center is difficult. However we were able to detect the ^{28}SiO, confirming qualitatively the previous results by Lindqvist et al. 1991, which were obtained with the Nobeyama 45m dish. The results are shown in Fig. 1. In the data centered on the ^{30}SiO lines there is no trace of any maser emission. Because the lines are the result of exponential amplification it is not possible to give a direct estimate of the upper limit of the ^{30}SiO abundance in OH359.762+01.20, but clearly no proof is found that OH359.762+0.120 is a TŻO. The nature of this OH/IR star remains a mystery.

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