Evolution of Accreting Neutron Star Common Envelopes and Their Nucleosynthesis - Possible P-nuclide Production

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Abstract. In a binary system, a short lived phase called a common envelope can occur in which both stars share the envelope of the primary. During this phase, there is the opportunity for nucleosynthesis to occur at high temperatures and densities in the accretion disk which forms around the secondary star. The system of interest is one in which the secondary star is a neutron star. After introducing the system, our model is described and preliminary results are presented. Preliminary simulations show that light p-nuclides $^{92}$Mo and $^{96,98}$Ru are overproduced, and that the closer the material is to the neutron star prior to ejection, the fewer p-nuclides are produced.

1 Introduction

In a binary system, a short phase can occur during which the two stars orbit within a common stellar envelope. This common envelope (CE) phase occurs as a result of Roche Lobe Overflow - for example when the primary star is expanding into its red giant phase - and the secondary accreting star cannot incorporate material quickly enough. The accretor is overwhelmed by the envelope of the expanding star and the two objects share an envelope. During the common envelope phase, the orbital energy of the binary is lost through dynamical and tidal friction. This results in the ejection of the primary’s envelope and the tightening of the binary’s orbit. This evolutionary stage is thought to be a vital step in the creation of compact binary systems such as neutron star mergers and X-ray binary systems [1].

In the scenario of interest here, the accretor is a neutron star and the expanding star is entering its red giant phase. Once inside the CE, the neutron star will slowly inspiral towards the core of the red giant while accreting hydrogen rich material at hypercritical rates [1], [3]. The angular momentum of the accreting material will cause it to hang up in an accretion disk. If the accretion rate is high, the temperature of this accreting material will become high enough to drive nuclear burning in the accretion disk as material approaches the neutron star [3]. A proportion of this material will then be ejected from the system, current hydrodynamical simulations say up to 25% [2]. When the material is ejected, it moves into the companion red giant. When the red giant ends its life as a supernova, the material which has undergone nucleosynthesis in the neutron star accretion disk can be ejected into the interstellar medium (ISM) [3].

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Figure 1. Schematic view of the path followed by material entering neutron star accretion disk.

Nucleosynthesis in the accretion disk of this system is not well understood. Keegans et al. (2019) conducted an initial investigation of the nucleosynthesis in accreting neutron star common envelopes using trajectories that assumed that the accreting material had no angular momentum. They find that this system could contribute to galactic chemical evolution (GCE) and find that in some simulations, some p-nuclides are overproduced. P-nuclides are a set of proton-rich isotopes ranging from $^{74}$Se to $^{196}$Hg - see Table 1 of [4]. In p-process models, p-nuclide isotopes are underproduced by a factor of four compared to Solar System abundances [5]. In particular, the isotopes $^{92,94}$Mo and $^{96,98}$Ru are underproduced by an additional order of magnitude compared to the other p-nuclides [5]. They are thought to be produced by the so-called p-process, where p-process is an umbrella term used to describe the processes which produce p-nuclides [6]. The possible sites hosting the p-process are debated.

Work presented here builds on the foundations laid by Keegans et al. (2019), improving upon them by using trajectories which account for the angular momentum needed to form an accretion disk.

2 Method

2.1 Accretion Disk Model

In order to model accretion around the neutron star, a modified Bondi-Hoyle-Lyttleton accretion model is used. This model is adapted from Popham et al. (1999), where they model hyperaccreting black holes [8]. In the model used here, the accretion rate is set to:

$$M_B \approx \lambda_{BHL} 4 \pi r_B^2 \rho (v^2 + c_s^2)^{\frac{1}{2}}.$$  \hspace{1cm} (1)

Where $\lambda_{BHL}$ is a non-dimensional scaling parameter to lower the accretion rate due to limiting factors such as angular momentum of the system or gradients in the accretion disk (see [9] for more details), $r_B$ is the Bondi radius, $v$ is the velocity of the material bound to the accreting object and $c_s$ is the speed of sound in the accreting material.

Figure 1 shows a schematic view of the trajectory followed by the material. The material infalls towards the neutron star. The angular momentum of the accreting material causes the formation of an accretion disk around the neutron star. New material joins the accretion disk at the outer edge, and loses angular momentum as it moves towards the centre of the accretion disk. During this process, material is ejected from the disk by a wind and moves back into the companion star. All through this process, the material is exposed to temperatures and densities which allow for nucleosynthesis to occur. We model this process by post-processing...
temperature-density trajectories representative of the material’s trajectories. Figure 2 shows temperature time and density time plots for the eight trajectories explored. Material in the accretion disk is ejected at different radii. As the material moves inwards in the accretion disk towards the neutron star, it is exposed to higher temperatures and densities (see Figure 2). Therefore, the material’s final composition depends on the innermost radius reached before ejection. We denote the point at which material is ejected from the accretion disk as the "inner radius", in units of cm. The smaller the inner radius is, the further into the accretion disk - closer to the neutron star - the material moves prior to ejection. In order to explore how the nucleosynthesis of p-nuclides is affected by the inner radius, we tested a set of eight trajectories with different inner radii. We can also explore the average production of p-nuclides over the eight trajectories, which taken together serve as an approximation of an accretion disk. To do this, we averaged the mass fraction of each p-nuclide over the trajectories. We then divided this average by the initial abundance of the p-nuclide to find the average overproduction from the approximated accretion disk.

2.2 Post-Processing Code - NuGrid

The post-processing code NuGrid was used to calculate the nucleosynthesis. The NuGrid run was a version of Modular2ininet3 adapted so that REACLIB was used to replace outdated rates, such as those from Iliadis et al. (2001) (see [11] for more details) [10], [11], [12]. The network was composed of 5200 isotopes. The initial abundances were solar scaled, and have a metallicity of $Z_m = 0.02$. This is to reflect the high hydrogen abundance in the accreting material.

3 Preliminary Results

Figure 3 shows the impact of varying the inner radius reached by the material on the production of p-nuclides. As the material moves closer to the neutron star before ejection - and the peak temperature and density reached increases (see Figure 2) - higher mass p-nuclides...
Figure 3. Effect of changing the inner radius on production of p-nuclides for a set of trajectories modelling accretion around a 1.5M\(_{\odot}\) neutron star at an accretion rate of 8 \times 10^{-5} M_{\odot}s^{-1}. Any isotopes which had an overproduction of less than –1 were not included.

Figure 4. Average overproduction of p-nuclides for an approximated accretion disk composed of eight trajectories modelling accretion around a 1.5M\(_{\odot}\) neutron star at an accretion rate of 8 \times 10^{-5} M_{\odot}s^{-1}. Are not overproduced in the final abundances. For the three smallest inner radii, only \(^{74}\)Se and \(^{78}\)Kr are overproduced. For all but the three closest inner radii, the isotopes \(^{96,98}\)Ru are consistently overproduced by 2 dex or more. The exception to this is \(^{96}\)Ru at inner radius 2.04 \times 10^{6} \text{cm}, where it is overproduced by just under 2 dex. For all but the three closest inner radii, \(^{92}\)Mo is overproduced and for all but the four closest inner radii it is overproduced by more than 1 dex. Exploration is ongoing to determine what prevents p-nuclides with A > 78 from being overproduced when the inner radius decreases and the material moves closer to the neutron star. A likely cause is that photodisintegration reactions are breaking down higher mass p-nuclides due to the higher temperatures reached at lower inner radii (see Figure 2 for more).
Figure 4 shows the average overproduction of p-nuclides for an approximated accretion disk. While $^{94}$Mo is underproduced, other light p-nuclides - $^{92}$Mo, $^{96,98}$Ru are overproduced by dex 1 and dex 2 respectively, as is the light p-nuclide $^{102}$Pd. Heavier p-nuclides are also overproduced, including the long lived radioisotope $^{138}$La. Figure 4 shows evidence that an approximation of an accretion disk can overproduce light p-nuclides, which are under-produced in current p-process models. Further work needs to be done to understand the nucleosynthesis at work in this system.

4 Conclusions

Initial results show that p-nuclides are overproduced in accreting neutron star common envelopes. In particular light, p-nuclides - $^{92}$Mo and $^{96,98}$Ru - which are usually underproduced in p-process models. This is significant as nucleosynthesis in accreting neutron star common envelopes has not been explored in great detail. In the future, we will investigate the nucleosynthesis in accretion disks on larger grids, explore the impact of parameters such as the angular momentum of the accreting material and the mass of the accretor. Work will also involve better understanding the affect of varying the metallicity of the accreting material, as well as placing any overproduction in the context of the ISM and GCE.

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References