Simulating Binary Star Systems to Test Our Models

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As a star burns through its fuel, it goes through many evolutionary changes. A major event is at the end of a stars life when it has burned through all of its fuel - the death of the star. Smaller stars (like our Sun) will undergo a planetary nebula and result in a white dwarf, a relatively peaceful death in stellar terms. For more massive stars however, starting at masses approximately 9 times that of our Sun, they will undergo a violent supernova explosion and can produce no remnant, a neutron star, or black hole. These explosions release a significant amount of energy which can be a substantial fraction compared to the total energy released throughout the stars life, Walch & Naab (2015). With such a considerable amount of energy produced, it is not surprising that the star could be launched at a high speed. We have observed newly born neutron stars moving at 100s of kilometres per second, and possibly even 1000 kilometres per second - Hobbs et al. (2005). These velocities are due to what we call a natal/asymmetric kick at birth, however the exact mechanism by which they occur is unknown.

Many systems are actually multi-star systems which house many star orbiting around each other - this makes our solar system quite a rarity. An interesting question is what happens when a star goes supernova in a binary system, a system with two stars. One outcome is the binary stars separate in the explosion. This commonly happens if more than half of the total system mass is lost in the supernova explosion - Boersma (1961). Sometimes the stars may collide and merge. The case I am interested in here is the case where the system survives - what happens to it? We know that the supernova kick must also occur in the binary - is there any difference in how it occurs here compared to for a single star? What velocities can these binary systems be launched at? Is there a relation between the velocity and some other parameter, for say, the mass of the star in the binary yet to die (from here called the companion star)? For this work, I am interested in binary systems containing a neutron star (formed by a so called "progenitor" going supernova) and a normal star, particularly one of a high mass - over approximately 8 times the mass of our Sun. These systems are called Neutron Star High-Mass X-Ray Binaries, as they contain a Neutron star, a high mass star, and emit Large amounts of X-Ray radiation. Figure 1 shows an artists impression of what one of these systems might look like, NASA/CXC/M.Weiss (NASA/CXC/M.Weiss). For this investigation of binaries, I require high quality data on the positions of binaries, their velocities, and their masses. The positional and part of the velocity data can be found from the *Gaia* (Gaia Collaboration et al. (2016)) † ‡ mission, and the most recent data release, DR3 (Gaia Collaboration et al. (2022)). The rest of the data that I cannot find within *Gaia* comes from previous literature. I use a data set of known Neutron Star High-Mass X-Ray binaries found by Fortin et al. (2022). Within is 17 star systems with all the data I require, of which I use 16 due to one system having a distance too unreliable for my usage. With the data in hand, next is to calculate the velocities of my systems. This is rather complex, as there are many extra sources of velocity that need to be removed. For example, the Milky Way is a spiral galaxy, so all star systems in its disk rotate around its centre. Figure 2 from Mróz et al. (2019) shows a graph of the rotation speed of the Milky Way compared to distance from its centre. I have to remove this source (and others) of velocity so that I only the velocity given by the asymmetric kick remains.

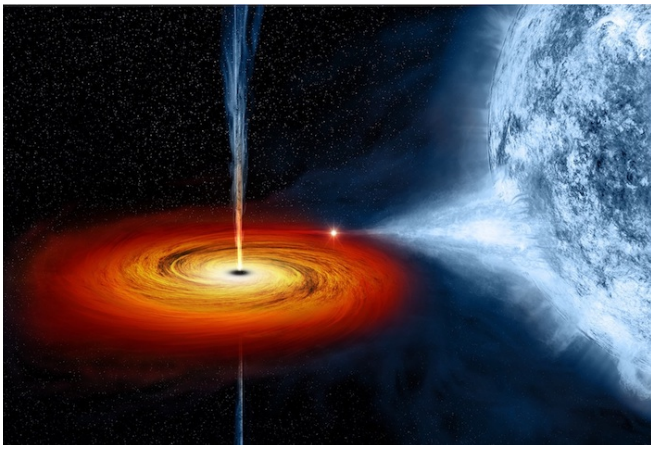

Figure 1. An artists impression of a High-Mass X-Ray Binary. You can see the massive companion star on the right with a black hole on the left. The black hole has a disc of mass around it, pulled from the companion star. There is also a jet coming from the top and bottom of the black hole. These two things are the source of the radiation from the x-ray binary.

Figure 2 shows my calculated velocities against the mass of the companion. The velocity increases with increasing companion mass. Analysing the data tells us that there is a moderate positive correlation which is statistically significant - unlikely to have arisen from pure chance. This result is confusing - more energy is required to accelerate more massive objects, so you would expect no, or even the opposite correlation.

A good way to test our current knowledge of asymmetric kicks in these systems is to perform simulations. If our current models of binary evolution and kicks are able to reproduce results seen from actual data, we should be able to explain what we see. Here, I simulate many binary systems using the software COSMIC, Breivik et al. (2020) §. There are many different values that I can change for

† https://www.cosmos.esa.int/gaia
‡ https://www.cosmos.esa.int/web/gaia/dpac/consortium
§ https://github.com/COSMIC-PopSynth/COSMIC

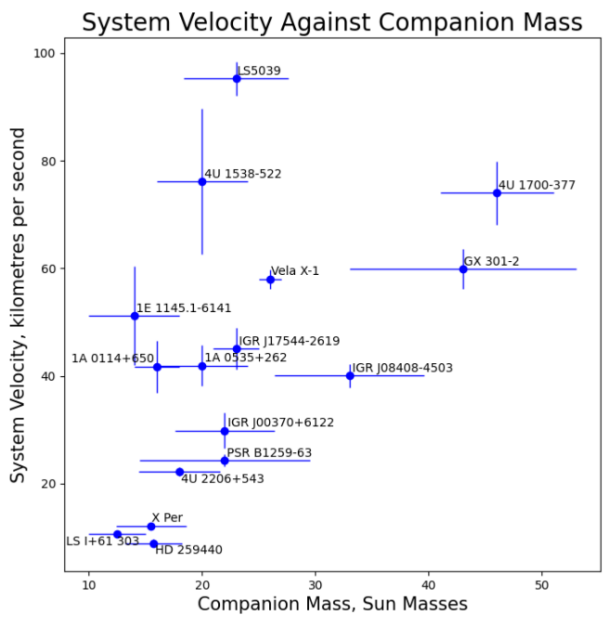

Figure 2. System Velocity in kilometres per second, against Companion Mass in Masses of the Sun.

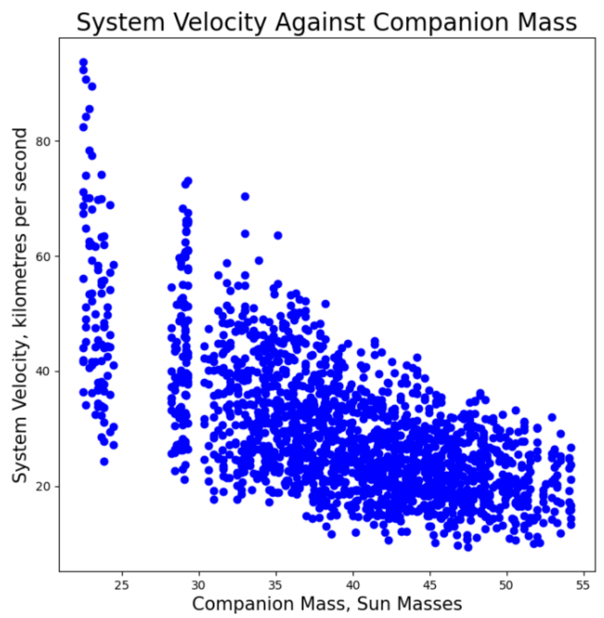

Figure 3. System Velocity in kilometres per second, against Companion Mass in Masses of the Sun. This plot was produced via simulation.

my systems - both of the star masses, the time it takes for the stars to orbit each other (their "orbital period"), how circular the orbit is, and many other more qualities pertaining to complex interactions. Due to limitations in computing power and time, I choose to only change two things at once. Figure 3 shows one such plot. This plot includes only the binaries that survived the supernova and produced a neutron star, equivalent to the systems from real data. Here, I changed the star masses while keeping a constant orbital period of 20 days. It is clear that the graph has the opposite relation between mass and system velocity which indicates that our models are wrong. There is also a massive gap around 25 Sun masses, which I will explain next.

The mass gap simply arises due to how I generated my systems. Due to time constraints, I could only generate a small number of initial masses, so I had a step size of 1 Sun mass. This naturally results in a gap at the lower end due to less combinations of initial masses being able to produce a certain final mass.

Next, the incorrect correlation. We know that our current model must be incorrect, however why is it? A potential answer is how the simulation software applies the asymmetric kicks to the systems. COSMIC does not simulate the internal physics of the kick, in fact it randomly draws a velocity from a set of velocities and applies it in a random direction to the newly formed neutron star. This set of velocities is calculated using past data on single, newly formed neutron stars and their velocities, the exact distribution of which can be seen in Hobbs et al. (2005). These velocities are then altered using some quantities to do with the newly formed star - namely, things to do with mass. There are 2 potential problems that you might see with this. First, the randomness might seem non-physical. In fact, there are many intrinsically random occurrences in physics - for example, radiation from radioactive material, and the ever mysterious quantum mechanics. In addition, this random drawing of velocities perfectly represents single neutron star velocities. This means that the fact that the velocities are "random" is irrelevant.

Now, for the randomly applied direction. We know that these neutron stars individually, much like planet Earth. There is evidence to suggest that kicks may be preferentially directed in the direction of the stars rotational axis. For example, they would be directed through the South Pole towards the North Pole, or vice versa in the case of Earth - Wang et al. (2006). This is something to test in the future as COSMIC allows you to implement this constraint.

The final reason could simply be that this single-star model for kicks does not work for binaries. The question is then why doesn't it work? It must be something specifically to do with binary evolution. A possible explanation is provided by van den Heuvel et al. (2000). We know that the Earth has many different layers - its crust, mantle, and core. We can split stars up like this too, however this explanation is due to the cores of the stars. van den Heuvel et al. (2000) find that larger stars typically have a different core that, through the life cycle of the binary, will cause the binary stars to more closely orbit each other. This can facilitate heavier systems having higher velocities. This interaction is not implemented in COSMIC, so perhaps doing so would cause it to produce a result more consistent with data.

REFERENCES

Boersma J., 1961, bain, 15, 291
Breivik K., et al., 2020, apj, 898, 71
Fortin F., García F., Chaty S., Chassande-Mottin E., Simaz Bunzel A., 2022, aap, 665, A31
Gaia Collaboration et al., 2016, aap, 595, A1
Gaia Collaboration et al., 2022, arXiv e-prints, p. arXiv:2208.00211
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, mnras, 360, 974
Mróz P., et al., 2019, apjl, 870, L10
NASA/CXC/M.Weiss, Illustration of Cygnus X-1, `https://chandra.harvard.edu/resources/illustrations/blackholes.html`
Walch S., Naab T., 2015, Monthly Notices of the Royal Astronomical Society, 451, 2757
Wang C., Lai D., Han J. L., 2006, apj, 639, 1007
van den Heuvel E. P. J., Portegies Zwart S. F., Bhattacharya D., Kaper L., 2000, aap, 364, 563