Bachelor Natuur- en Sterrenkunde (jd)

Bachelor thesis

On the Kinematical Properties of High-mass X-ray Binaries using *Gaia* DR2

by

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6 July, 2018

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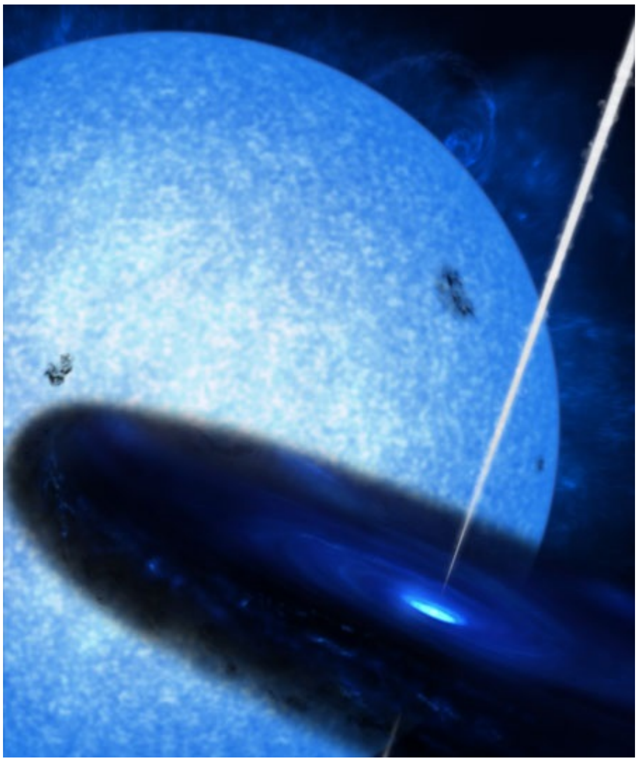

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Abstract

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Submission date: 6 July, 2018
Conducted between 2 April, 2018 and 6 July, 2018.

Cover image: Artist impression of the High-mass X-ray binary Cyg X-1. Astronomical Illustrations and Space Art, by Fahad Sulehria, `www.novacelestia.com`.

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1. Introduction

The main goal of this thesis is to research the kinematical properties of high-mass X-ray binaries (HMXB). The research of HMXBs is important because it can be used in different branches of Astronomy and Astrophysics. For one, HMXBs can be used as an indicator of star formation in galaxies [12]. It is also possible to determine the properties of the thin and thick disk of the Milky Way using HMXBs [11].

As Blaauw [5] has shown, there exist O and B type stars with unexpected large peculiar velocities, so called runaway stars. Two scenarios are able to explain these high velocities. The first one is a supernova explosion in a massive binary [5] and the second one is the dynamical ejection model [19]. Hoogerwerf et al. [15] has shown, using Hipparcos data, that the supernova scenario is more common than the dynamical ejection model. Since massive OB runaway stars can be used to study the interstellar medium (ISM) [16] and since the supernova scenario predicts that all HMXBs should be runaway stars, it is important to research the peculiar space velocities of these HMXBs.

To research the kinematical properties of HMXBs we make use data obtained during the Gaia mission. The Gaia mission is a collaboration of the European Space Agency (ESA) and is the successor to the Hipparcos mission. The Gaia spacecraft was launched on 19 December 2013 and began collecting data on 19 July 2014 [10]. Gaia measures the positions of stars with submilliarcsecond precision over time. These accurate measurements of the positions of the stars make it possible to determine the parallax and the proper motions, the so called five-parameter astrometry [13]. The parallax of a star and the error on the parallax make it possible to calculate a confidence interval of the distance between the Sun and the star [4]. All the raw data from the Gaia spacecraft has been processed by the Gaia Data Processing and Analysis consortium (DPAC) [10]. The first data release, *Gaia* DR1, was made public on 14 September 2016. The second and most recent data release was made public on 25 April 2018. This thesis makes use of *Gaia* DR2. A third and fourth data release are planned for 2020 and 2022.

Several scientific questions will be answered in this thesis. We are going to look at the difference between the peculair space velocities of OB-supergiant and Be/X-ray binaries. OB-supergiant systems should have systematically higher space velocities than Be/X-ray systems, according to van den Heuvel et al. [22]. Knigge et al. [18] has the hypothesis that Be/X-ray binaries with lower spin periods should have lower space velocities than systems with a high spin period. At last we will look at the height distribution of HMXBs within the Milky Way and a comparison with Grimm et al. [11] will be made.

2. High-mass X-ray Binaries

High-mass X-ray binaries (HMXB) are systems which consist of a neutron star or a black hole and a high-mass companion. These high-mass companions are usually an O or B type stars with a mass greater than $10\,M_\odot$. While uncommon, there exist HMXBs in which the companion is an A or WR type star [24].

A massive binary system is needed to produce a HMXB [21]. Less than 50% of the total system mass needs to be lost for the system to remain bound after the primary star goes supernova [1]. This is possible if there was a phase of mass transfer from the primary to the secondary before the primary went supernova. What is left after the supernova explosion is a neutron star or stellar black hole with a, now heavier, O or B type star.

X-ray emission occurs when mass lost from the companion accretes on the compact object. In the majority of HMXBs the accretion is due to stellar wind [24]. These are the systems in which the luminosity is lowest. A higher luminosity is found in systems in which the compact object travels through the circumstellar disk of a Be type star, so called X-ray transient systems. The luminosity of these systems is highest at periastron [6]. In the (super) giant systems the companion fills the Roche lobe and the majority of the accretion is due to tidal effects on the companion. This is not the same as Roche lobe overflow. Roche lobe overflow is extremely rare in HMXBs and is confirmed in only one system in the Milky Way, Cen X-3 [23].

The angular distribution of HMXBs follows the spiral structure of the Milky Way [11]. The height above the galactic plane of HMXBs is much smaller than that of low-mass X-ray binaries (LMXB). HMXBs follow an exponential disk with a scale height of 150 pc while LMXBs have a scale height of 410 pc [11].

HMXBs are not limited to the Milky Way. A large number of HMXBs lie in the Large Magellanic Cloud (LMC) and the Small Magellanic Cloud (SMC). The number of HMXBs in the LMC is comparable with the number of HMXBs in the Milky Way, when corrected for the masses of the galaxies [18]. The number of HMXBs in the SMC is remarkable. It is approximately the same number as that of the Milky Way, even though the mass of the SMC is about 100 times smaller than that of the Milky Way. It is suspected that this is due to a star formation burst 60 Myr ago [14].

3. Distance and Space Velocities

3.1. Determination of Distance

The Gaia DR2 catalogue gives the parallax and the one sigma error on the parallax for more than one billion stars. However, the DPAC has decided to leave the estimated distance to those stars out of the official Gaia DR2 catalogue [3]. The Gaia catalogue gives the parallax, ϖ, and the error on the parallax, σ_ϖ, in milliarcseconds (mas). The equation to calculate the distance d, in kpc, given by

$$d = \frac{1}{\varpi}, \tag{3.1}$$

can only be used if there is no error on the parallax. Since there is an error on the parallax, estimating the distance with this method is naive according to C. A. Bailer-Jones [4]. Equation 3.1 should only be used when:

$$\frac{\varpi}{\sigma_\varpi} > 5 \tag{3.2}$$

In this thesis there are a lot of cases where $1 \leq \frac{\varpi}{\sigma_\varpi} \leq 5$. To get the most accurate estimated distance it is needed to use a weak distance prior and Bayesian statistics [3][4]. Since the transformation from parallax to distance is asymmetric it is also needed to calculate a confidence interval of the estimated distance.

3.1.1. Distance catalogue

C. Bailer-Jones et al. [3] have calculated the estimated distances and their confidence intervals for all sources in Gaia DR2 with a measured parallax and error on the parallax. They made their own catalogue which is publicly avaiable. To get the calculated distances it is needed to query the catalogue using the Astronomy Data Query Language (ADQL) at `http://gaia.ari.uni-heidelberg.de/tap.html`. A used query to determine the distance to a well known HMXB, Vela X-1, can be found below:

```
SELECT source_id, r_est, r_lo, r_hi
FROM gaiadr2_complements.geometric_distance
JOIN gaiadr2.gaia_source USING (source_id)
WHERE source_id = 5620657678322625920
```

The result of this query can be found in Table 3.1.

source_id	r_{est} pc	r_{lo} pc	r_{hi} pc
5620657678322625920	2415.10654483993	2250.86167997563	2604.40481475367

Table 3.1.: An example of a distance table produced by the distance catalogue of the HMXB Vela X-1 [3]. The estimated distances are given in parsecs and r_{lo} and r_{hi} are the lower and upper bounds of the 68% confidence interval.

The query gives us the source id, the estimated distance, r_{est}, and the lower and upper bounds of the 68% confidence interval, r_{lo} and r_{hi}. The distances are given in parsec. The source id is an unique integer for all the stars in Gaia DR2. The determination of the source ids of the HMXBs used will be discussed later. The results of the query can be saved as a comma seperated value (.csv) file. The .csv files can be imported in Python for analysis.

3.2. Space velocities

To calculate the peculiar transverse velocities and the peculiar space velocities, we have made use of a Python program which was created by Jari van Opijnen in May 2018. Some adaptions to the program were made to make it possible to calculate the peculiar transvere velocities of HMXBs.

The Python program takes the position, proper motions, radial velocity, estimated distance and their errors as arguments. The position and proper motions are taken from the official Gaia DR2 catalogue. The estimated distance, and the lower and upper bounds of the 68% confidence interval (C.I.) are taken from the complementairy catalogue described in subsection 3.1.1. The radial velocity and the error on the radial velocity are taken from the SIMBAD astronomical database (Simbad) [7]. Some HMXBs, for example QV Nor, do not have an error on the radial velocity even though the radial velocity itself is given. Whenever this is the case, the program assumes a radial velocity error of 2.0 km/s. This value was chosen in this thesis because it was the average of the error of the radial velocities of the HMXBs for which this error was known.

The positions and proper motions of the HMXBs are transformed from the International Celestial Reference System (ICRS) to galactic coordinates and proper motions. This was done using matrix algebra as described in Evans et al. [8]. The expected motions due to the solar motion and the galactic differential rotation were calculated using the model made by Jari van Opijnen. It is based on the work of Fich et al. [9] which assumes the following: stars follow circular orbits around the galactic center, there are no vertical gradients and the sun lies directly in the galactic plane. The difference between the expected proper motions and the measured proper motions, combined with the estimated distance, gives us the peculiar velocity of the HMXB. The program calculates the peculiar transverse velocities of all HMXBs, and the peculiar space velocities for all HMXBs with a known radial velocity.

3.2.1. Absence of radial velocities

For the majority of the HMXBs used in this thesis, the radial velocity is unknown. The radial velocity of a HMXB can be determined by taking a high resolution spectrum. Using the spectrum, it is possible to determine the (Doppler) redshift and thus the radial velocity. However, since all HMXBs are binaries, the spectrum is not constant with time and depends on the orbit of the HMXB.

To get the correct radial velocity it is needed to determine the center of mass velocity, γ. To do this, measurements of the radial velocity of different stages of the orbit are needed. This can be difficult since the orbital period of a HMXB can be longer than one year[1] [24]. To illustrate this, the radial velocity curves of LS I +61 303 and LS 5039, both HMXBs, are given in Figure 3.1.

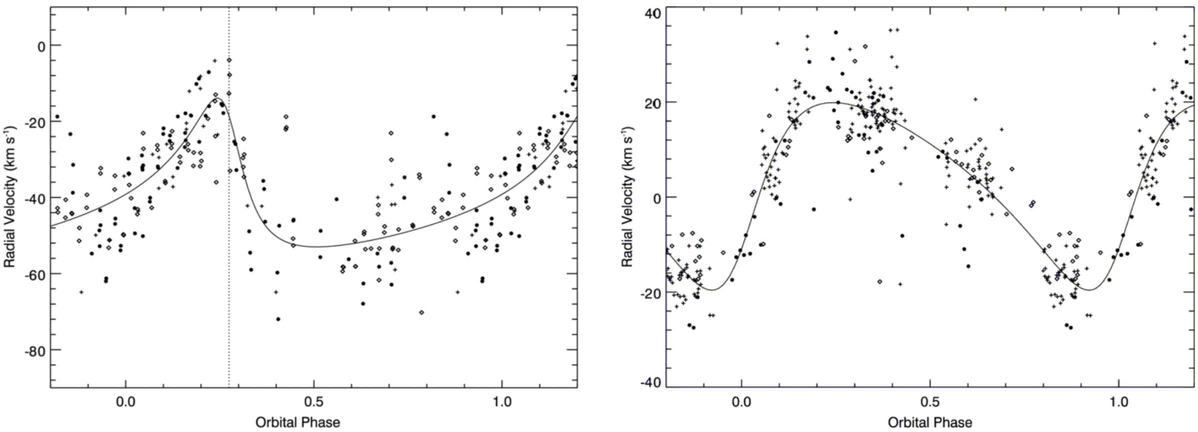

Figure 3.1.: The radial velocity cuves of LS I +61 303 (left) and LS 5039 (right). Figures taken from Aragona et al. [2]. The radial velocity changes with the orbital phase. The shape of the line depends on the eccentricity and inclination of the orbit.

Figure 3.1 shows that the radial velocity depends on the orbital phase. Aragona et al. [2] determine a γ-value of $(-41.41 \pm 0.60)\,\mathrm{km/s}$ for LS I +61 303 and a γ-value of $(4.01 \pm 0.31)\,\mathrm{km/s}$ for LS 5039.

When the radial velocity of a HMXB is unknown we can only calculate the peculiar transvere velocity. Even though the peculiar transvere velocity is not the true runaway speed, it can be used to get an indication of the real peculiar space velocity.

[1]The orbital period of the HMXB XTE J1858+034 is 380 Days.

4. OB-supergiant X-ray binaries and Be/X-ray binaries

4.1. Introduction

There is a systematic difference between the runaway velocities of OB-supergiant X-ray Binaries and Be/X-ray Binaries. In 2000 van den Heuvel et al. [22] show that, on average, OB-supergiant X-ray binaries have higher runaway velocities than Be/X-ray binaries. This was done using a sample consisting of four OB-supergiant systems and eleven Be/X-ray systems. Since radial velocities were unavailable van den Heuvel et al. [22] calculate the peculiar transvere velocities of these fifteen systems. They find a mean peculiar transvere velocity, $\langle v_{tr} \rangle$, of (42 ± 14) km/s for the OB-supergiant systems and a $\langle v_{tr} \rangle$ of (15 ± 6) km/s for the Be/X-ray binaries. This is in agreement of the models that explain the formation of these systems. The higher runaway velocities of OB-supergiant systems is a combination of two things: (1) higher pre-supernova orbit velocities than those of the Be/X-ray binaries. This is due to the shorter orbital period which is caused by the larger fractional helium core masses in the progenitors of the compact object [22]. (2) Less mass is ejected in the supernova of the Be/X-ray systems compared to the OB-supergiant systems.

van den Heuvel et al. [22] made use of the proper motions and parallaxes measured by the predecessor of the Gaia mission: the Hipparcos mission. With the release of *Gaia* DR2 this is a unique moment to redo the research. Combining the proper motions with the radial velocities avaiable we can calculate the true peculiar runaway velocities of the OB-supergiant en Be/X-ray systems.

4.2. Sample creation

The sample was created using Simbad. A query was made to return all objects in Simbad with the maintype equal to High-mass X-ray binary. This results in 1423 objects. Objects with unknown spectral type or spectral type without a 'B' or 'O' are discarded. We are left with 202 objects. The HMXBs from the SMC and LMC are discarded aswell.

The objects left in the sample are looked up at (1) `http://simbad.u-strasbg.fr/simbad/sim-fbasic` and (2) `http://gaia.ari.uni-heidelberg.de/singlesource.html`. (1) Was used to look up the Johnson-Cousins V magnitude [17]. (2) Is an online tool created by the Gaia Collaboration. Since the Gaia catalogue does not make crossmatches, the crossmatches were done by me. The Gaia tool (2) takes the coordinates of the object from Simbad and returns the twenty closest sources observed by Gaia. The Gaia G magnitude of the closest source was compared with the Johnson-Cousins V magnitude. If the difference between V and G was deemed to great, the object was discarded. Jordi et al. [17] describe the expected differences between V and G. While V and G are different magnitudes, they almost have the same value[1]. Lastly we look at the parallax and the error on the parallax. Objects with $\varpi > 0$ and $\frac{\varpi}{\sigma_\varpi} > 1.0$ were kept. The source id given by (2) was noted together with the Simbad main id.

We are left with 49 objects. 17 of these objects have a known radial velocity in Simbad. The following query was made to the Gaia catalogue to download all the data:

```
SELECT source_id, ra, ra_error, dec, dec_error, pmra,
pmra_error, pmdec, pmdec_error, parallax, parallax_error,
r_est, r_lo, r_hi, phot_g_mean_mag FROM
gaiadr2_complements.geometric_distance JOIN
gaiadr2.gaia_source USING (source_id) WHERE source_id =
5620657678322625920 OR source_id = 5333660129603575808 OR ...
```

4.3. Results

For all the 48 objects the peculiar transvere velocity was calculated. For the 17 objects with known radial velocity the peculiar runaway velocity was also calculated. Figure 4.1 plots the peculiar transvere velocity against the galactic longtitude. On average, the Be/X-ray systems have a lower velocity than the OB-supergiant systems. For three HMXBs their errorbar exceeds the plotted region. From left to right these HMXBs are: 2MASS J18453684+0051474, 2E 2336 and QV Nor. This is due to their relative large uncertainties on their parallaxes and thus the estimated distance. This is illustrated in Table 4.1.

Figure 4.2 shows the peculiar runaway velocity against the galactic longtitude. It becomes clear that the OB-supergiant systems have, on average, higher runaway velocities compared to Be/X-ray binaries. The errorbar of QV Nor exceeds the plotted region. X Per is plotted in black. X Per is the Be/X-ray binary with the highest velocity, but it is also the Be/X-ray binary with the highest mass [24].

4.4. Conclusions

Figure 4.1 and especially Figure 4.2 show that that the velocities of OB-supergiant systems are, on average, higher compared to Be/X-ray binaries. This is in agreement with

[1] For the sample used we found $\langle$V - G$\rangle$ = 0.4875.

Object	ϖ (mas)	σ_{ϖ} (mas)	r_{est} (kpc)	r_{lo} (kpc)	r_{hi} (kpc)	G mag.
J18453684+0051474	0.41	0.35	2.3	1.3	4.2	18.7
2E 2336	0.21	0.19	3.6	2.3	6.1	18.5
QV Nor	0.07	0.05	6.6	5.2	8.8	13.2

Table 4.1.: Parallaxes and estimated distances of three inaccurate HMXBs. The 68% C.I. spans several kpc.

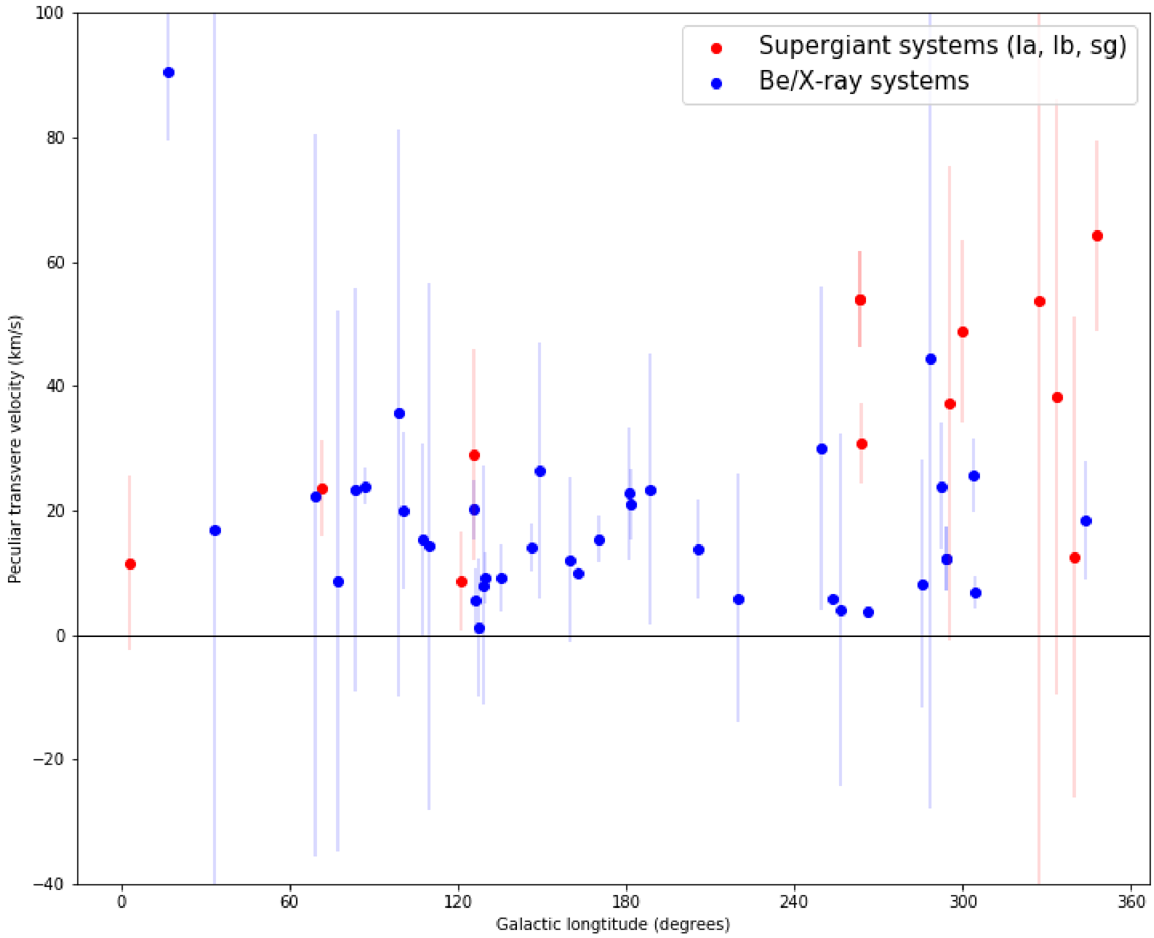

Figure 4.1.: The peculiar transvere velocity plotted against the galactic longtidude. It is shown that on average Be/X-ray systems have lower peculiar transvere velocities than OB-supergiant systems. For three HMXBs the errorbar exceeds the plotted region. These objects are, from left to right: 2MASS J18453684+0051474, 2E 2336 and QV Nor.

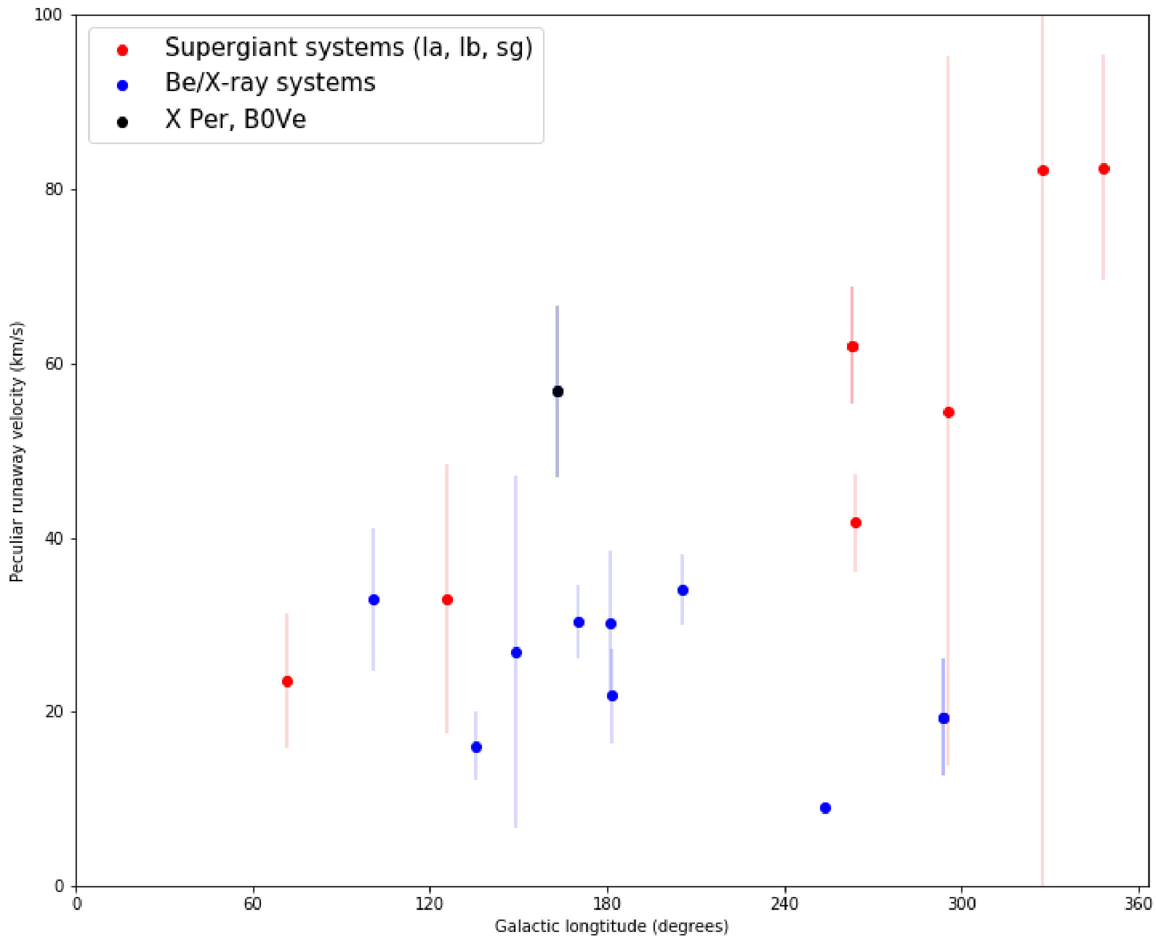

Figure 4.2.: The peculiar runway velocity plotted against the galactic longtidude. It is shown that OB-supergiant systems, on average, have higher peculiar runaway velocities than Be/X-ray binaries. The errorbar of QV Nor exceeds the plotted region. X Per (black) is the Be/X-ray binary with the highest velocity but also the Be/X-ray binary with the highest mass [24].

van den Heuvel et al. [22]. The mean peculiar runaway velocity, $\langle v_{run} \rangle$, is (50 ± 15) km/s for the OB-supergiant binaries and $\langle v_{run} \rangle$ is (28 ± 7) km/s for the Be/X-ray binaries. These values are higher compared to van den Heuvel et al. [22]. This is expected since van den Heuvel et al. [22] calculates the two-dimensional peculiar transvere velocity and we calculated the three-dimensional peculiar runaway velocity. QV Nor has been left out of the calculations of $\langle v_{run} \rangle$ due to the large uncertainties in the estimated distance.

5. Be/X-ray Binaries

5.1. Introduction

Knigge et al. [18] report that there are two distinct populations in Be/X-ray binaries (BeXB). These populations are produced by two different types of supernova. One population is produced by a iron-core-collapse supernovae while the other is produced by a electron-capture supernovae. The first one is caused by an imploding degenerate iron core with a mass above the Chandrasekhar limit. The second type of supernovae is produced by an imploding lower mass core consisting of oxygen-neon-magnesium which loses its pressure due to the abrupt capture of electrons in the nuclei of magnesium and neon [18]. Knigge et al. [18] find a bimodality in both the spin period (of the neutron star) and the orbital period (of the binary system). This was done by collecting the spin and orbital periods of all BeXBs available, including the BeXBs in the SMC and LMC. They find a double-Gaussian in both spin and orbit periods. For the spin period peaks are found in the distributions at $P_{spin} = 10\,\mathrm{s}$ and $P_{spin} = 200\,\mathrm{s}$. The dip is found at $P_{spin} = 40\,\mathrm{s}$. The orbital period peaks at $P_{orb} = 40\,\mathrm{d}$ and $P_{orb} = 100\,\mathrm{d}$ with a dip at $P_{orb} = 60\,\mathrm{d}$. These values do not change significantly if they check for bimodality in BeXBs in exclusively the SMC or the Milky Way.

Knigge et al. [18] mention that if BeXBs with low spin periods are formed by low-kick-velocity electron-capture supernovae these systems should have systematically lower space velocities compared to BeXBs with a long spin period and suggest that this should be tested in further research. To test this prediction we need the peculiar transvere velocities or the peculiar runaway velocities of BeXBs combined with their spin periods. We can calculate the peculiar velocities as explained in Section 3.2. For the spin periods we turn to the available literature.

5.2. Sample creation

Since the prediction of Knigge et al. [18] is only valid for BeXBs, we must create a new sample. We make use of the online catalogue "Be/X-Ray Binaries and candidates in the Galaxy" which can be accessed at `http://xray.sai.msu.ru/~raguzova/BeXcat/`. The catalogue was made by Raguzova & Popov [20] in 2005 and is updated frequently. The catalogue contains confirmed BeXBs and BeXB candidates. It consists of 76 entries. While there is some overlap between the catalogue and the sample used in Section 4.2 there are new objects in this sample. This is because some of the entries in the catalogue

Object	ϖ (mas)	σ_ϖ (mas)	r_{est} (kpc)	r_{lo} (kpc)	r_{hi} (kpc)	G mag.
V2246 Cyg	0.15	0.11	3.6	2.7	5.0	16.9
V490 Cep	0.05	0.02	10.2	8.5	12.3	13.8
J18453684+0051474	0.41	0.35	2.3	1.3	4.2	18.7

Table 5.1.: Parallaxes and estimated distances of three inaccurate Be/X-ray binaries. The 68% C.I. spans several kpc.

have their maintype as Be star in Simbad.

The procedure described in Section 4.2 is repeated for the catalogue. The source id, object name, spectral type, spin period and orbital period were noted[1]. The criteria are met for 34 objects. Of those 34 objects, 19 have a known spin period and 15 have a known orbital period. Ten objects have a known radial velocity but there are only three BeXBs with known radial velocity and spin period: X Per, HD 245770 and HD 102567. It is decided to only calculate the peculiar transvere velocities.

5.3. Results

The peculiar transvere velocity is plotted against the spin period and the orbital period. A histogram is made of the peculiar transvere velocity. Figure 5.1 shows that the peculiar transvere velocity decreases with increasing spin period. Three BeXBs have an errorbar which exceeds the plotted region. These BeXBs are, from left to right: 2MASS J18453684+0051474, V2246 Cyg and V490 Cep. This is due large uncertainties in the estimated distances. The 68% C.I. is listed in Table 5.1. Figure 5.1 shows the BeXBs with a spin periods below 410 s.

Figure 5.3 shows the peculiar transvere velocity as a function of orbital period. V2246 Cyg has an errorbar greater than the plotted region. Lastly, a histogram of the peculiar transvere velocity is made in Figure 5.4 with binsizes of 5 km/s. Peaks are found in the bins of 5 km/s to 10 km/s and 20 km/s to 25 km/s.

5.4. Conclusions

Figure 5.3 shows that there is no clear correlation between the peculiar transvere velocity and orbital period. Knigge et al. [18] do not predict a colleration between these two parameters.

Two peaks are found in the histogram shown in Figure 5.4. This is interesting because Knigge et al. [18] also find clear peaks and a dip in the histogram of the spin and orbital

[1] The source id is from `http://gaia.ari.uni-heidelberg.de/singlesource.html`. The object name, spectral type, spin and orbital period are taken from the catalogue [20].

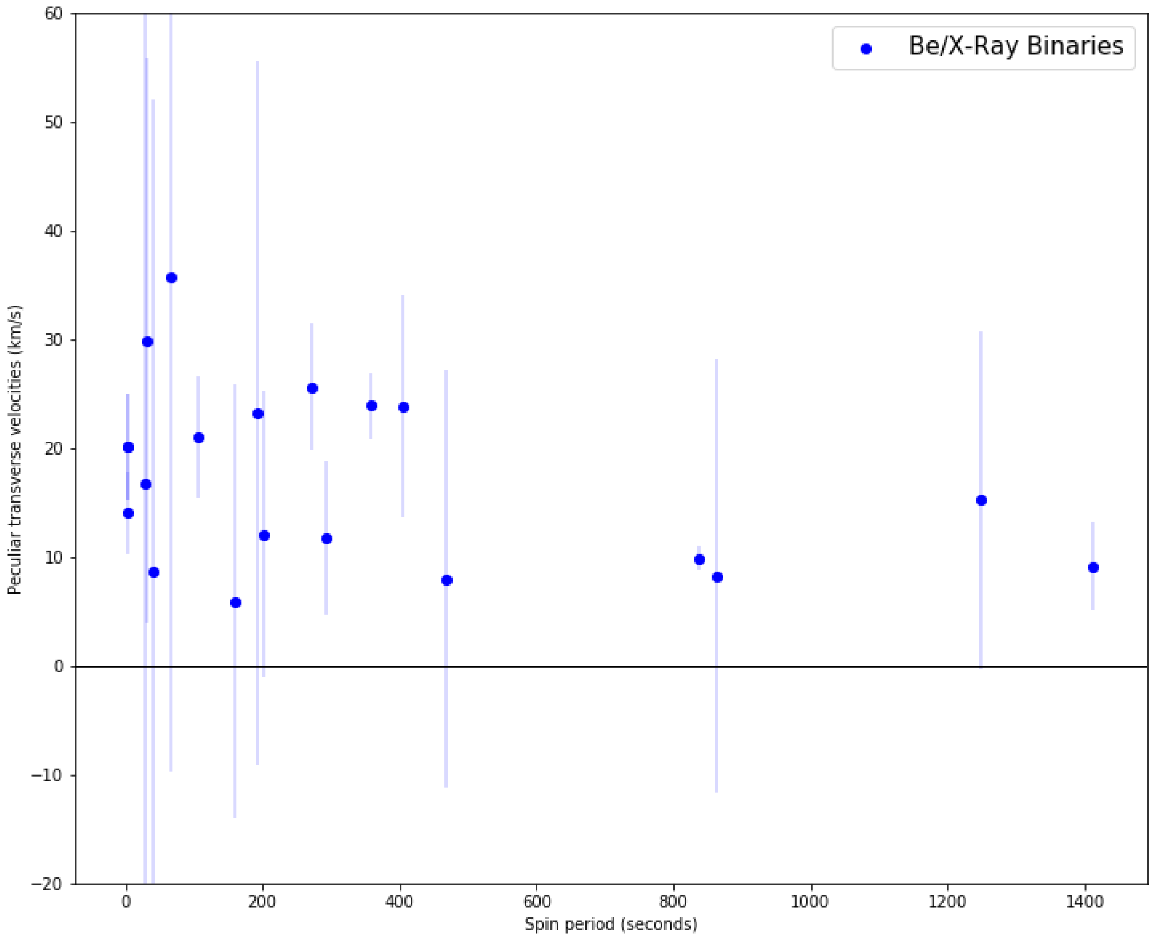

Figure 5.1.: The peculiar transvere velocities of the BeXB plotted against the spin period of the neutron star. Three BeXBs have an errorbars greater than the plotted region. These are, from left to right: 2MASS J18453684+0051474, V2246 Cyg and V490 Cep. The peculiar space velocity decreases with increasing spin period.

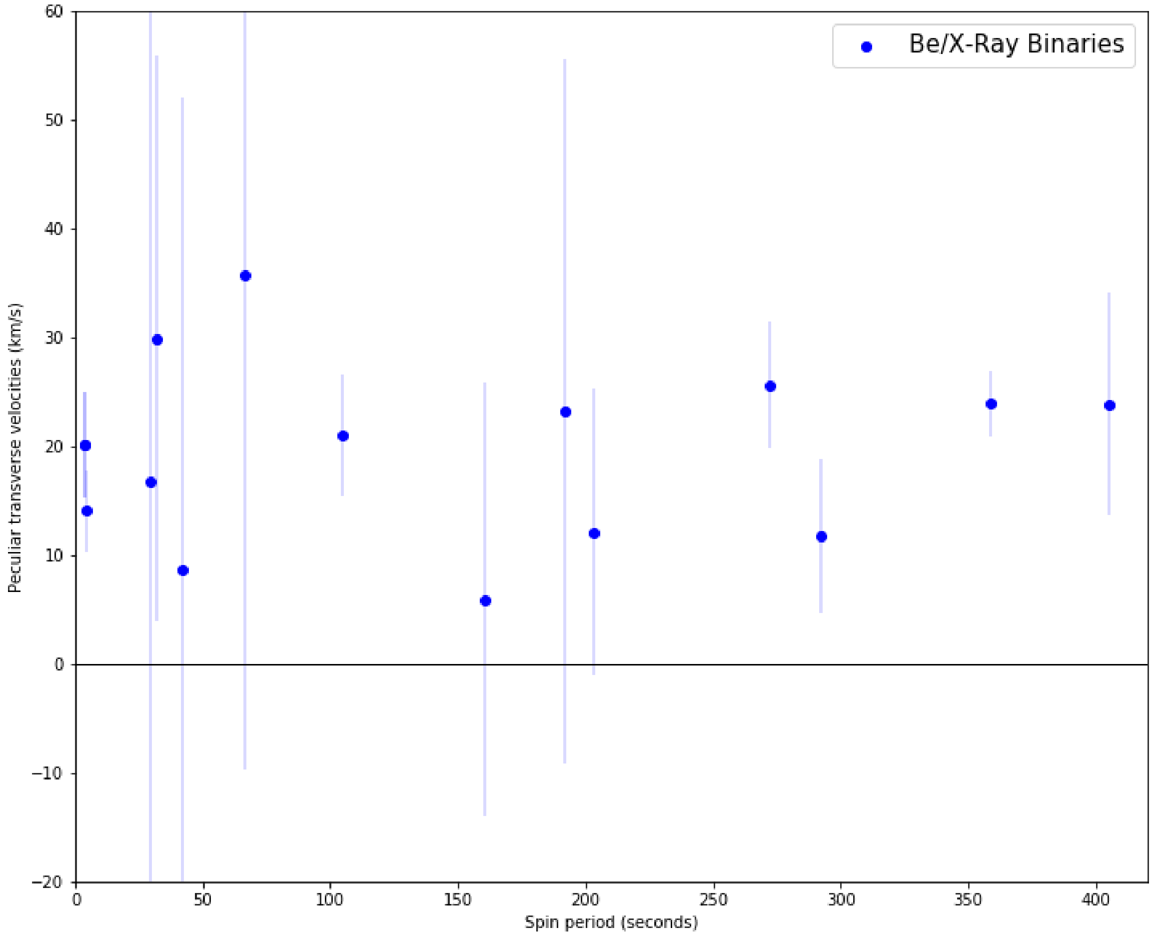

Figure 5.2.: Peculiar transvere velocities of BeXBs plotted against the spin periods of the neutron star in the region $P_{spin} < 420$ seconds.

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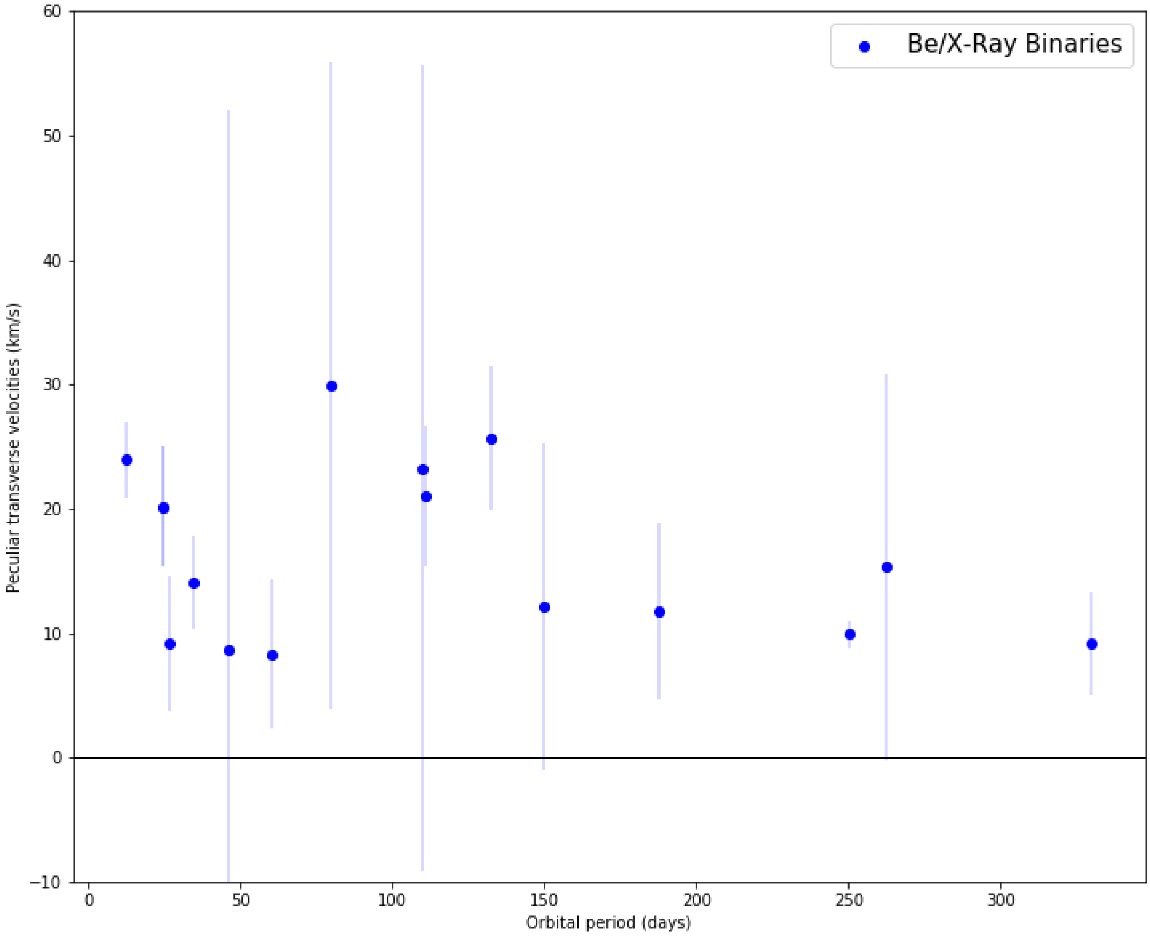

Figure 5.3.: The peculiar transvere velocities of the BeXB plotted against the orbital period of the BeXB system. No clear colleration can be found.

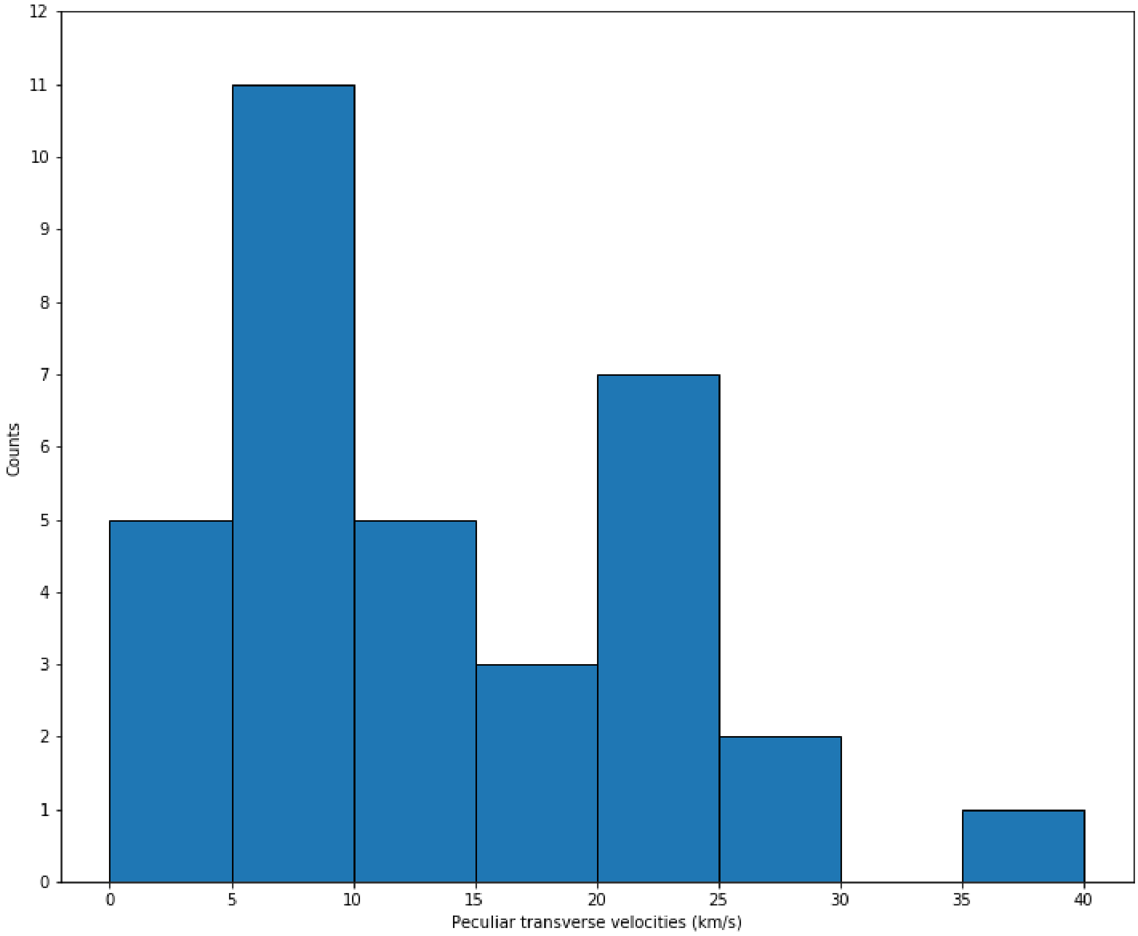

Figure 5.4.: Histogram of the peculiar transvere velocities with a bin size of 5 km/s. Peaks are found between 5 km/s to 10 km/s and 20 km/s to 25 km/s.

period. The peaks in Figure 5.4 can indicate that there is a bimodality in the peculiar velocities of BeXBs, just as there are bimodalities in the spin and orbital period [18].

As a final conclusion, Figure 5.1 and Figure 5.2 show that the spin period and the peculiar transvere velocity are disproportional. This is the exact opposite of what Knigge et al. [18] predict. No explanation can be given for this effect.

6. Distance and Height of HMXBs

6.1. Distance

...

6.2. Height

...

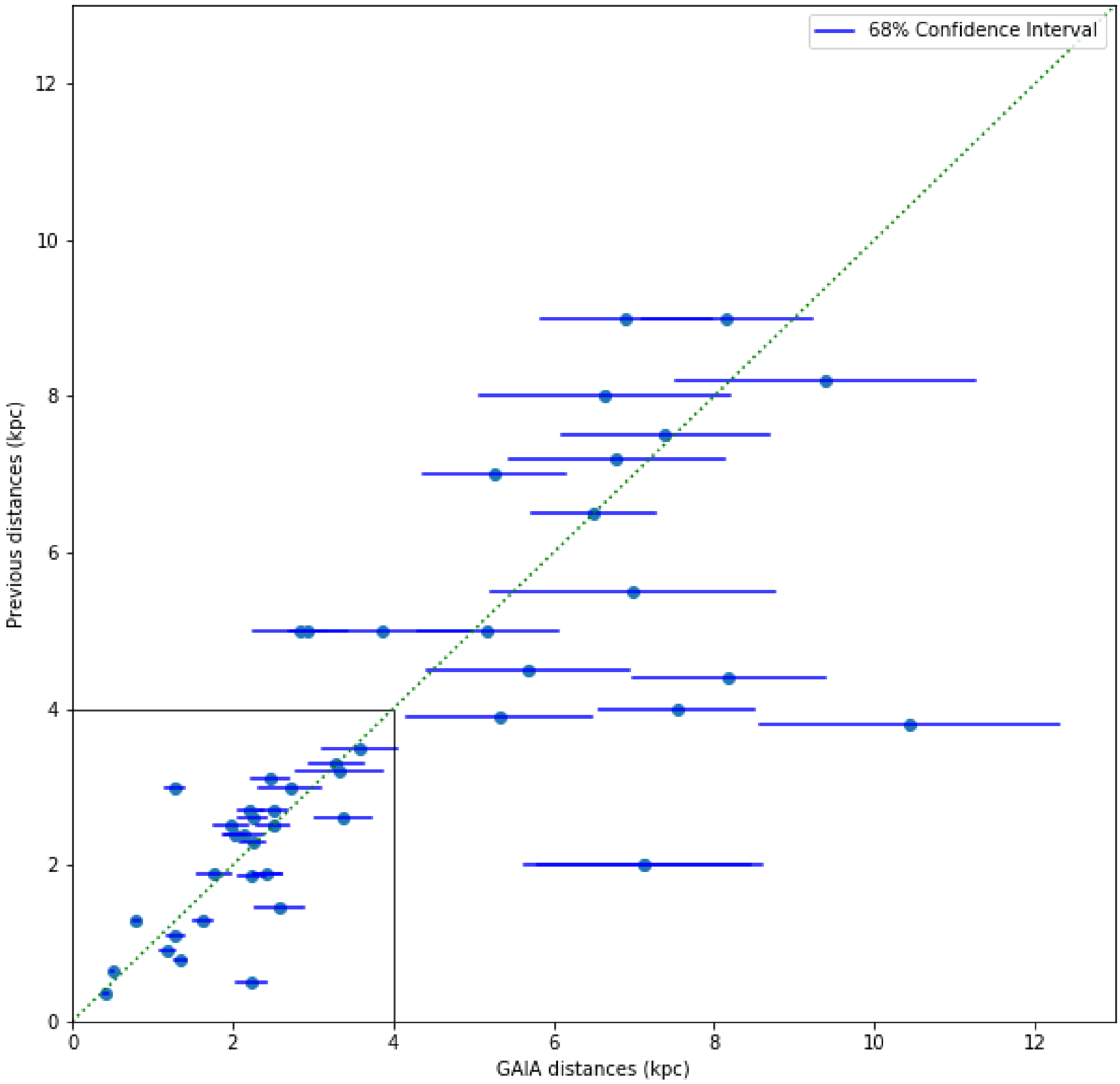

Figure 6.1.: Comparison of the estimated distances versus the distance found in literature before 2016. Each dot is a HMXB with the 68% confidence interval. Some intervals overlap, for example at a previous distance of 5 kpc. Objects below the dotted green line are further than previous estimated and vice versa.

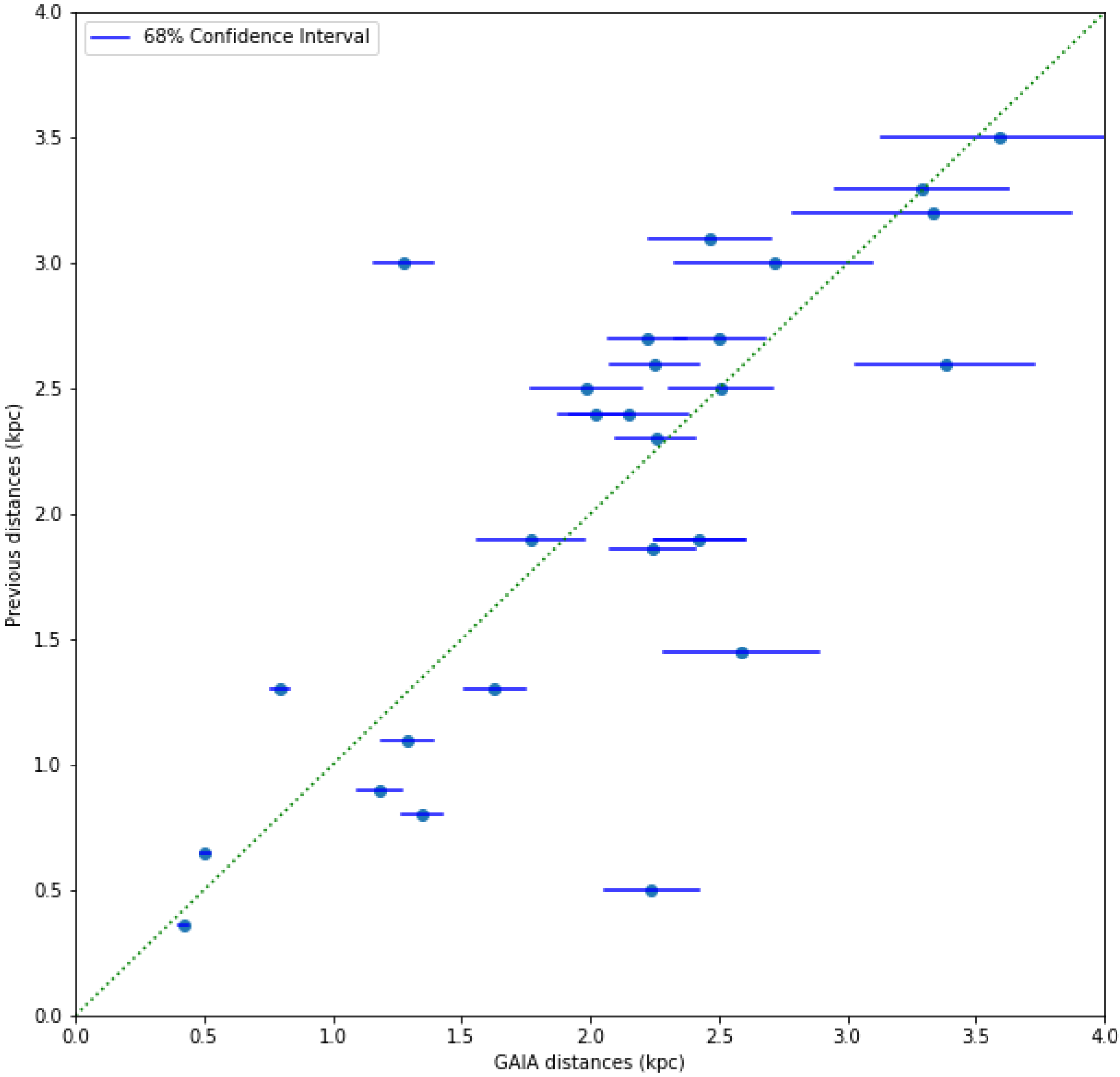

Figure 6.2.: Zoomed in version of Figure 6.1 in the region of 4 kpc.

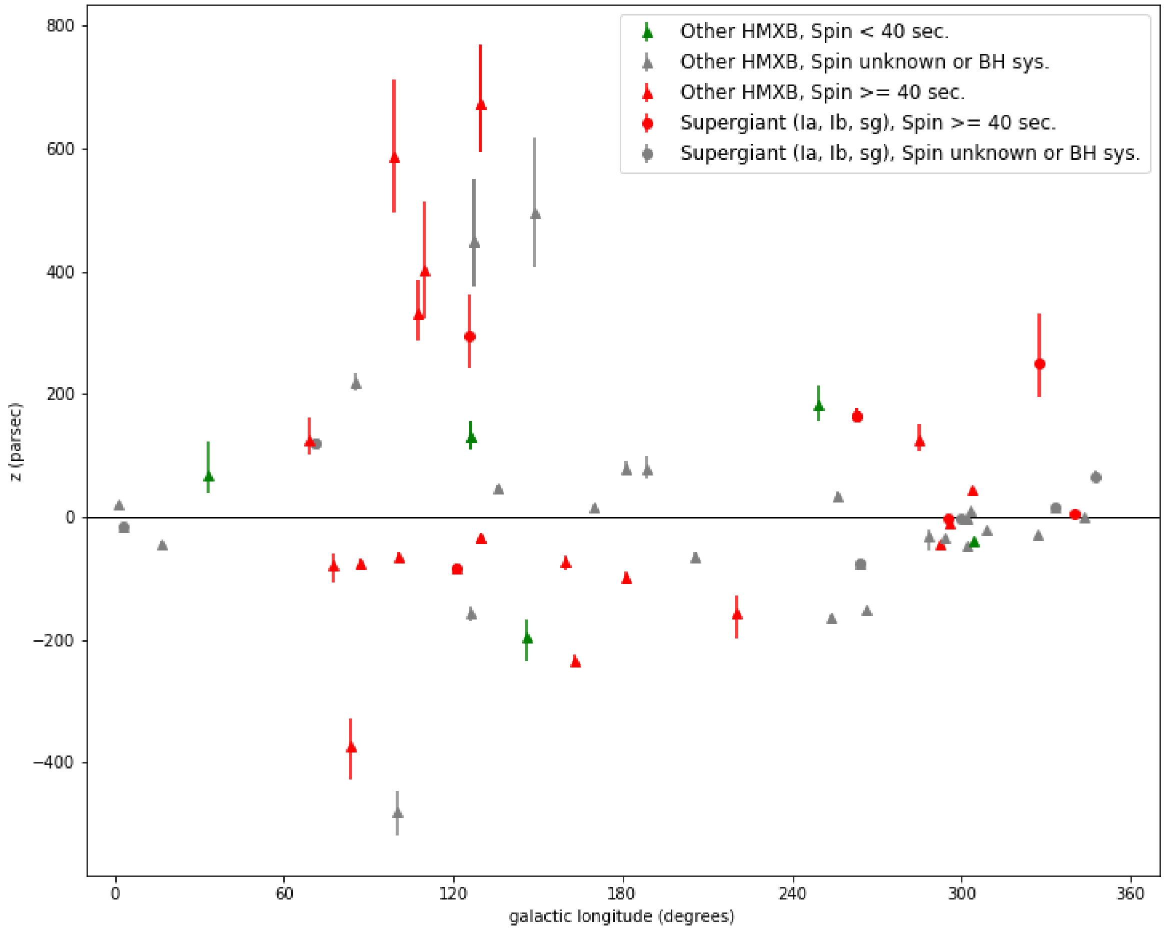

Figure 6.3.: The height above the galactic plane for HMXBs. Distinctions were made between Supergiant HMXBs and regular HMXBs, and between fast and slow spin periods. Grey objects are either Black Hole systems, or the spin period for the neutron star is undetermined.

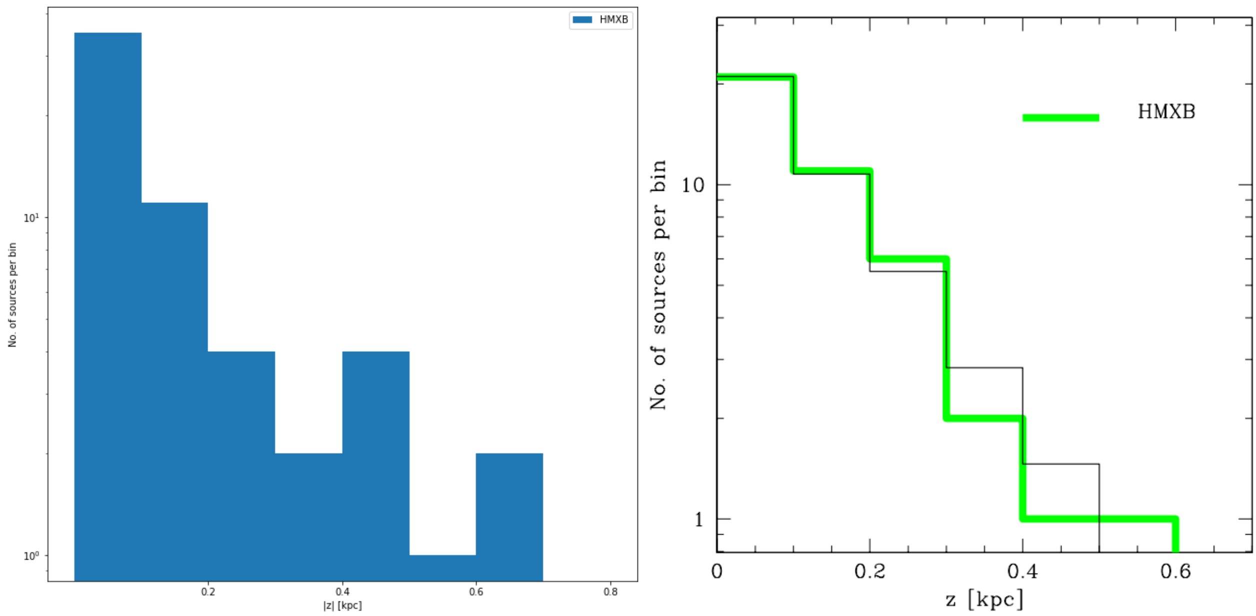

Figure 6.4.: Histogram of $|z|$. A Comparison has been made between HMXBs used in this thesis (left) and the results from Grimm et al. [11] (right).

7. Discussion

Hoe kunnen we dit onderzoek beter en nauwkeuriger maken? Systematische fout verkleinen dmv meer weten te komen over de solar motion zeggen dat dit natuurlijk een model is, en dat de LSR op elke plek turbulenties kan hebben. Daarom zou runaway snelheid eigenlijk bepaald moeten worden door te kijken naar de OB assiociaties waar deze sterren vandaan komen. Voor meer objecten de radiele snelheid en de fout hierop vinden. Door te kijken naar de lichtkracht en de nieuwe afstanden. Zijn al deze objecten in werkelijkheid wel OB sterren? Of staan ze dichterbij dan we dachten en is hun absolute lichtkracht een stuk minder?

Geen statistische test gedaan op de bimodaliteit van peculiar space velocities van BeXBs. De KKM test zou hier gedaan voor kunnen worden. ... Speed Cyg X-1 lower than expected. V* V479 Sct = LS 5039 and does have a radial velocity and a remarkable high peculiar transvere velocity.

8. Acknowledgements

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References

Ankay, A., Kaper, L., De Bruijne, J., Dewi, J., Hoogerwerf, R., & Savonije, G. (2001). The origin of the runaway high-mass x-ray binary hd 153919/4u1700-37. *Astronomy & Astrophysics*, *370*(1), 170–175.

Aragona, C., McSwain, M. V., Grundstrom, E. D., Marsh, A. N., Roettenbacher, R. M., Hessler, K. M., ... Ray, P. S. (2009). The orbits of the γ-ray binaries ls i+ 61 303 and ls 5039. *The Astrophysical Journal*, *698*(1), 514.

Bailer-Jones, C., Rybizki, J., Fouesneau, M., Mantelet, G., & Andrae, R. (2018). Estimating distances from parallaxes iv: Distances to 1.33 billion stars in gaia data release 2. *arXiv preprint arXiv:1804.10121*.

Bailer-Jones, C. A. (2015). Estimating distances from parallaxes. *Publications of the Astronomical Society of the Pacific*, *127*(956), 994.

Blaauw, A. (1961). On the origin of the o-and b-type stars with high velocities (the" run-away" stars), and some related problems. *Bulletin of the Astronomical Institutes of the Netherlands*, *15*, 265.

Drave, S., Bird, A., Sidoli, L., Sguera, V., Bazzano, A., Hill, A., & Goossens, M. (2014). New insights on accretion in supergiant fast x-ray transients from xmm–newton and integral observations of igr j17544- 2619. *Monthly Notices of the Royal Astronomical Society*, *439*(2), 2175–2185.

Egret, D., Wenger, M., & Dubois, P. (1991). The simbad astronomical database. In *Databases & on-line data in astronomy* (pp. 79–88). Springer.

Evans, D., Riello, M., De Angeli, F., Carrasco, J., Montegriffo, P., Fabricius, C., ... others (2018). Gaia data release 2.

Fich, M., Blitz, L., & Stark, A. A. (1989). The rotation curve of the milky way to 2 r (0). *The Astrophysical Journal*, *342*, 272–284.

Gaia Collaboration and others. (2016). The gaia mission. *arXiv preprint arXiv:1609.04153*.

Grimm, H.-J., Gilfanov, M., & Sunyaev, R. (2002). The milky way in x-rays for an outside observer-log (n)-log (s) and luminosity function of x-ray binaries from rxte/asm data. *Astronomy & Astrophysics*, *391*(3), 923–944.

Grimm, H.-J., Gilfanov, M., & Sunyaev, R. (2003). High-mass x-ray binaries as a star formation rate indicator in distant galaxies. *Monthly Notices of the Royal Astronomical Society*, *339*(3), 793–809.

Hambly, N., Cropper, M., Boudreault, S., Crowley, C., Kohley, R., de Bruijne, J., ... others (2018). Gaia data release 2.

Harris, J., & Zaritsky, D. (2004). The star formation history of the small magellanic cloud. *The Astronomical Journal*, *127*(3), 1531.

Hoogerwerf, R., De Bruijne, J., & De Zeeuw, P. (2000). The origin of runaway stars. *The Astrophysical Journal Letters*, *544*(2), L133.

Huthoff, F., & Kaper, L. (2002). On the absence of wind bow-shocks around ob-runaway stars: Probing the physical conditions of the interstellar medium. *Astronomy & Astrophysics*, *383*(3), 999–1010.

Jordi, C., Gebran, M., Carrasco, J., de Bruijne, J., Voss, H., Fabricius, C., ... Mora, A. (2010). Gaia broad band photometry. *Astronomy & Astrophysics*, *523*, A48.

Knigge, C., Coe, M. J., & Podsiadlowski, P. (2011). Two populations of x-ray pulsars produced by two types of supernova. *Nature*, *479*(7373), 372.

Poveda, A., Ruiz, J., & Allen, C. (1967). Run-away stars as the result of the gravitational collapse of proto-stellar clusters. *Boletin de los Observatorios Tonantzintla y Tacubaya*, *4*, 86–90.

Raguzova, N., & Popov, S. B. (2005). Be–x-ray binaries and candidates. *Astronomical & Astrophysical Transactions*, *24*(3), 151–185.

Van den Heuvel, E., & Heise, J. (1972). Centaurus x-3, possible reactivation of an old neutron star by mass exchange in a close binary. *Nature Physical Science*, *239*(92), 67.

van den Heuvel, E. P., Zwart, S. F. P., Bhattacharya, D., & Kaper, L. (2000). On the origin of the difference between the runaway velocities of the ob-supergiant x-ray binaries and the be/x-ray binaries. *Arxiv preprint astro-ph/0005245*.

Van der Meer, A., Kaper, L., Van Kerkwijk, M., Heemskerk, M., & van den Heuvel, E. (2007). Determination of the mass of the neutron star in smc x-1, lmc x-4, and cen x-3 with vlt/uves. *Astronomy & Astrophysics*, *473*(2), 523–538.

Walter, R., Lutovinov, A. A., Bozzo, E., & Tsygankov, S. S. (2015). High-mass x-ray binaries in the milky way. *The Astronomy and Astrophysics Review*, *23*(1), 2.

A. Complete tables

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