Study of Accretion Effects of Transients in LMXB System

By Quentin Lamicq

A Senior Project presented to the

Physics Department at

California Polytechnic State University, San Luis Obispo

June 2010

Abstract

Neutron stars are intriguing stellar laboratories that are very exciting to study due to the presence of matter in an extreme state. The luminosity of some neutron star transients in low mass X-ray binary (LMXB) systems is known to have quiescent intervals that may be affected by the rate and duration of accretion from the companion star onto the neutron star. We refined a model of the luminosity of the neutron star to allow for possibility that the accretion rate declines at a steady rate until it reaches zero. After a neutron star goes through an outburst, the quiescent period has a higher luminosity if a longer accretion decay length is used. The luminosity does not vary if the accretion decay is exponential or linear. The present model does not match observation of well-known neutron star transient KS 1731-260.

Background

Structure of the Neutron Stars

The neutron star was first theorized in 1933, shortly after the discovery of the neutron, but the existence was not confirmed until 1967 [3]. Neutron stars can form either from the core collapse of a massive supernova or from accretion induced collapse of a white dwarf in a binary system [4]. The central density of a neutron star is around 10^{15} g cm^{-3}. A typical neutron star has mass of more than 1.4 $M_{\odot}$ but not more than 3 $M_{\odot}$ with a radius of around 20 km [3]. The mechanism for keeping such a large amount of mass in such a star is degenerate neutron pressure. For a static isolated neutron star, the temperature on the surface of the neutron star is cooler than in the inside. This means that the inside of the neutron star can be thought of as in a thermodynamic equilibrium [5]. There is evidence that neutron stars are superfluid and superconductive [3]. The interior of a neutron star can be divided into several distinctive regions as shown in Figure 1. The innermost structure is called the core of the star. The makeup of the inner core is unknown but could be composed of superfluid neutrons with pions and kaons or strange particles [4]. Directly outside the inner core is the outer core, which is composed of superfluid neutrons and protons. Just outside the core is a region called the inner crust, which is composed of degenerate neutrons and nuclei. The boundary between the inner crust and outer crust is a border where neutrons can not exist in β-equilibrium [1]. This last region occupies about 1 km of the neutron star and weighs around 0.01 solar mass.

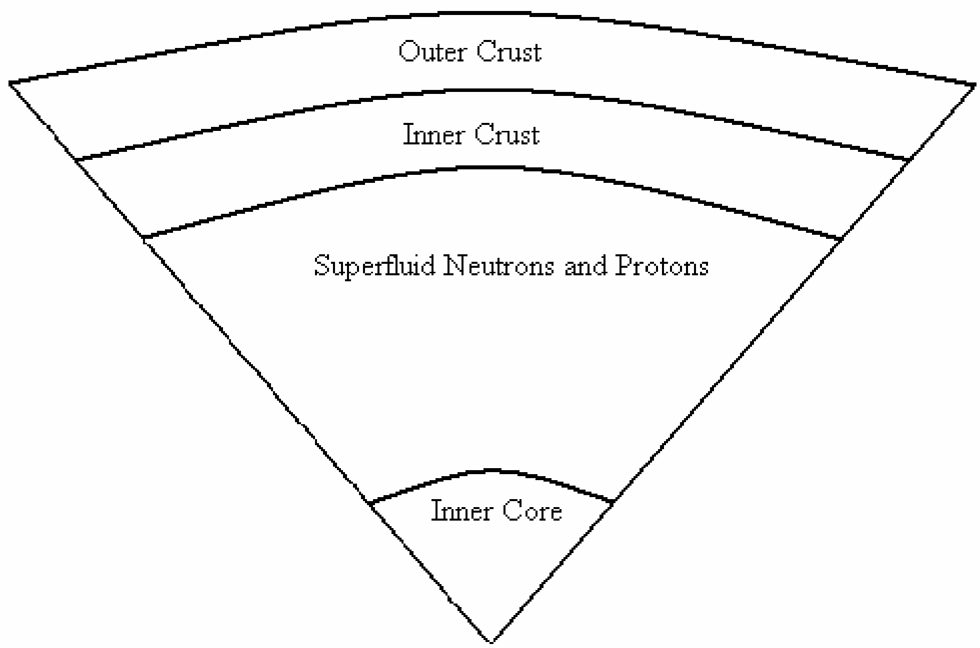

Figure 1. Internal structure of neutron star showing the different layers of the neutron star.

Binary systems/Accreting Neutron Stars

The low mass X-ray binary (LMXB) systems are composed of a neutron star and main sequence or slightly evolved star. The accretion of material from the companion star to the neutron star happens when the companion star gets big enough to fill its Roche lobe and spills material over the Lagrangian point [2]. The distance between the neutron star and the companion star is around 0.01 to 1 AU [3]. The rate at which accretion happens is around 10^{15}-10^{18} g s^{-1}, approximately 10^{-9} $M_{\odot}$ per year. The material that passes the Roche lobe point is then subject to the conservation of angular momentum, so the material does not fall directly to the surface but piles up in a disk [5]. The material then falls to the surface of the star, releasing gravitational energy in the process. The neutron star emits large amounts of X-rays in hot spots as the material from the star is drawn onto the magnetic poles. If the accretion rate is zero, the neutron star is still visible due to the slow release residual heat from within a neutron star.

Transients

A transient neutron star describes a star where the decrease in luminosity is believed to be due to the shutoff of accretion. A low luminosity quiescent state occurs when the accretion in the binary system may decline or even stop. A star exhibits outbursts when the luminosity of the star increases suddenly due mainly to accretion. The outburst of these stars can last anywhere from hours to centuries [5]. Since the accretion does not necessarily have to be zero for the neutron star to be in a low luminosity quiescent state, a good rule of thumb to identify one of these is that it should drop 3 times in its luminosity [3]. An example of a transient star is KS 1731-260, a neutron star that went into quiescence after 12 yrs of sustained outburst activity [2]. It is currently in a quiescent state. KS 1731-260 was first discovered in August of 1989 using the *Mir-Kvant* telescope [2]. It was at first very luminous, but in 2001 the luminosity dropped considerably leading to the assumption that accretion had ceased. Observations of KS 1731-260 taken with the *Chandra* X-Ray telescope showed that the luminosity at 0.1 yr after accretion had stopped was 4.6×10^{33} erg s^{-1} and at 0.7 yr, 1.2×10^{33} erg s^{-1} [12]. A typical neutron star in outburst usually has a luminosity of around $\sim 10^{36}$ erg s^{-1}. We will compare our model to observations of KS 1731-260, looking for clues to the interior of the star.

Model

Model purpose

This model is a theoretical representation of the luminosity of a neutron star assuming that the accretion rate is not constant. The luminosity curves calculated with this program can be compared to observational data to see if different methods of accretion have a realistic impact on the luminosity of the neutron star following outburst.

Description of Model

In this model, the luminosity of the neutron stars was calculated using coherent thermodynamic principles including thermonuclear and pycnonuclear processes. We studied the effects of the accretion rate on the luminosity of the neutron star. The maximum accretion rate in this model was set at 1 x 10^{15} g s^{-1}. Some of the types of processes that were included were high conductivity electron - phonon interaction, standard neutrino emission, and enhanced neutrino emission. Neutrino emission is an effective way to lower the temperature of the star as neutrinos diffuse directly to the outside carrying energy away in the process [5]. Neutrino emission near the crust is dominated by Bremsstrahlung [5]. Standard neutrino emission can happen in the crust of the neutron star and is given by the reaction:

$$n + n \rightarrow n + p + e^{-} + \bar{v}_e \quad (1)$$

$$n + p + e^{-} \rightarrow n + n + v_e \quad (2)$$

Enhanced neutrino emission is given by the reaction:

$$n \rightarrow p + e^{-} + \bar{v}_e \quad (3)$$

$$p + e^{-} \rightarrow n + v_e \quad (4)$$

The difference between the two reactions is that the standard neutrino emission can happen anywhere in the star while the enhanced neutrino emission can only occur in the core of the neutron star as the proton fraction is too low. Both of these methods effectively help in decreasing the temperature of the neutron star and increase the luminosity of the star. However, at temperatures ~10^9 K, the direct Urca process is 5-6 times more efficient than the modified Urca process [5]. During previous study of these processes it was shown that the enhanced neutrino emission coupled with the high conductivity crust was closest to the shape of the decreasing luminosity for KS 1731-260 [2]. This method of core neutrino emission was used in this model.

Changes to the model

The main difference between the older model and the new model is that the older one did not assume a decreasing accretion rate. The accretion rate during an outburst for the old model stayed the same for a period of yrs and then dropped to zero in a step function. In this model, the outburst accretion rate was constant for a number of specified years, and then declined slowly until it reached zero. This decline was modeled as either a linear decline or an exponential decline. When a new cycle starts, the start of accretion was still assumed to be a step function. The outburst accretion length is variable and is specified by the user. The accretion decay length is also specified for a number of years. It decline until it hits an accretion rate of zero. At this point, the accretion rate reaches its quiescent interval and is now zero for the remainder of the cycle. Since an exponential function can never reach zero, a tolerance variable was used to define when it steps down to zero. The tolerance variable was fixed at 1% of the original accretion rate. If the accretion rate hits one percent of its original value for the exponential decay, then it will automatically go to zero for the rest of the accretion decay time.

Aspects of Model

In modeling the star KS 1731-260, a cycle of 1500 yrs was assumed. Of those 1500 yrs, twelve of them had accretion at the full rate. The variation in the models happens for different accretion decay rates, *ac*. The base model that all models were compared to is that there is no accretion decay rate, *ac* = 0. A second model had a short accretion decay rate of 24 yrs. A third model had a medium accretion decay rate of 500 yrs. A fourth model performed was with a long accretion decay rate of 1487 yrs. In each of these accretion rate decays, two models were run, one for linear decay and the other for exponential decay. For each model, the crust was first run into a steady state by running the program for 10 cycles. The next cycle following the 10 cycles was used as the comparison to observation.

Results

Since the program used was set up for no accretion decay length at first, a run was done to compare with other graphs that have accretion decay length. Figure 2 illustrates what happens to the luminosity of the neutron star when the accretion suddenly shuts off. The accretion used was 12 yrs with 1488 yrs of the neutron star in a quiescent state. As can be seen, the luminosity remains constant over a long period of time until it starts declining a little. There is no significant change in the luminosity over these 1488 yrs of quiescent state. In all plots, Lq is given for KS 1731-260 on the lower left hand side. Observation from KS 1731-260 showed that the luminosity at 0.1 yr after accretion had stopped was 4.6 x 10^{33} erg s^{-1} and 0.7 yr, 1.2 x 10^{33} erg s^{-1} [8].

Figure 3 shows the luminosity of the star if there were 12 yrs of accretion, 12 yrs of accretion decay, and 1476 yrs of no accretion. The data was graphed for both a linear and exponential

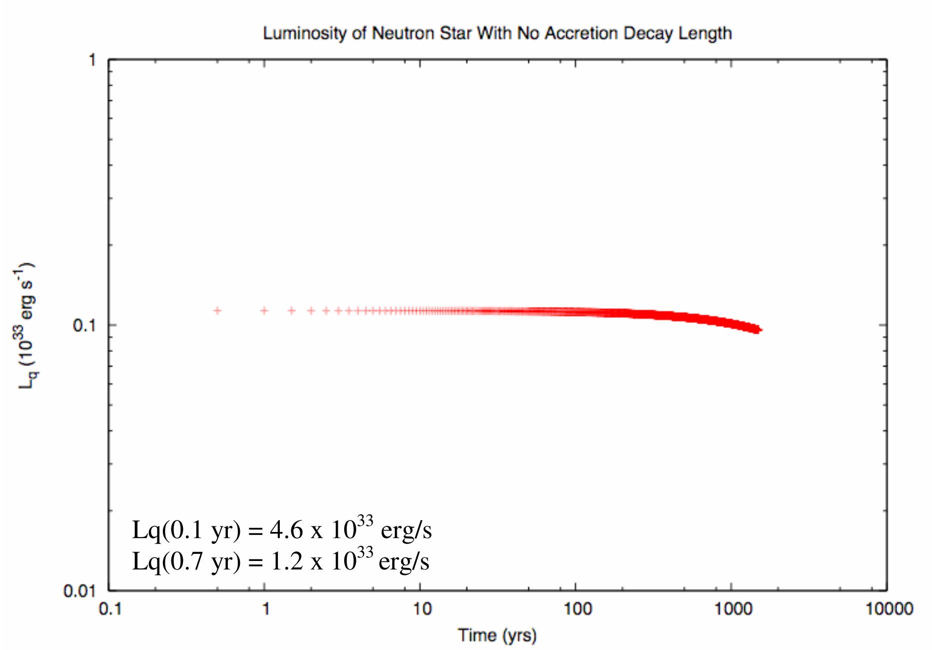

Figure 2. Luminosity of neutron star if there is no accretion decay length.

function as a function of time after the first 12 yrs of accretion. This model shows a drop in the luminosity after the accretion decay has finally stopped. If a linear accretion decay is used, the luminosity when the star is in its quiescent period is slightly higher then the exponential model. The shapes of the graphs are relatively the same throughout and the luminosity still drops a little bit lower at the end of the cycle. Comparing Figure 2 and Figure 3, the luminosity in the quiescent state is higher for the 12 yrs of accretion decay.

Figure 4 shows what happens if the accretion decay length is 500 yrs. The luminosity actually increases while the neutron star accretion rate is decreasing. This is most likely due to continued nuclear processes combining with residual heat in the crust. There is not much difference between the exponential and linear, although a difference can be observed in the shape of the luminosity increase. After the decay has stopped, the luminosity lowers to about what it is in Figure 3. The next graph shows what would happen if the neutron star never had accretion rate of zero.

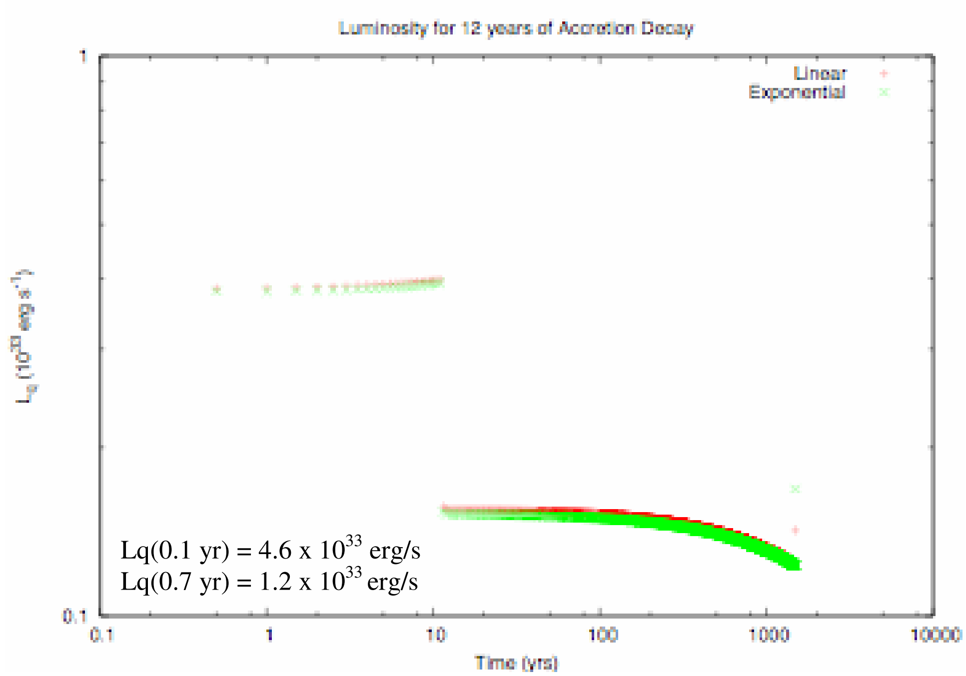

Figure 3. Luminosity of neutron star assuming 12 yrs of accretion decay length after accretion at full outburst has shut off.

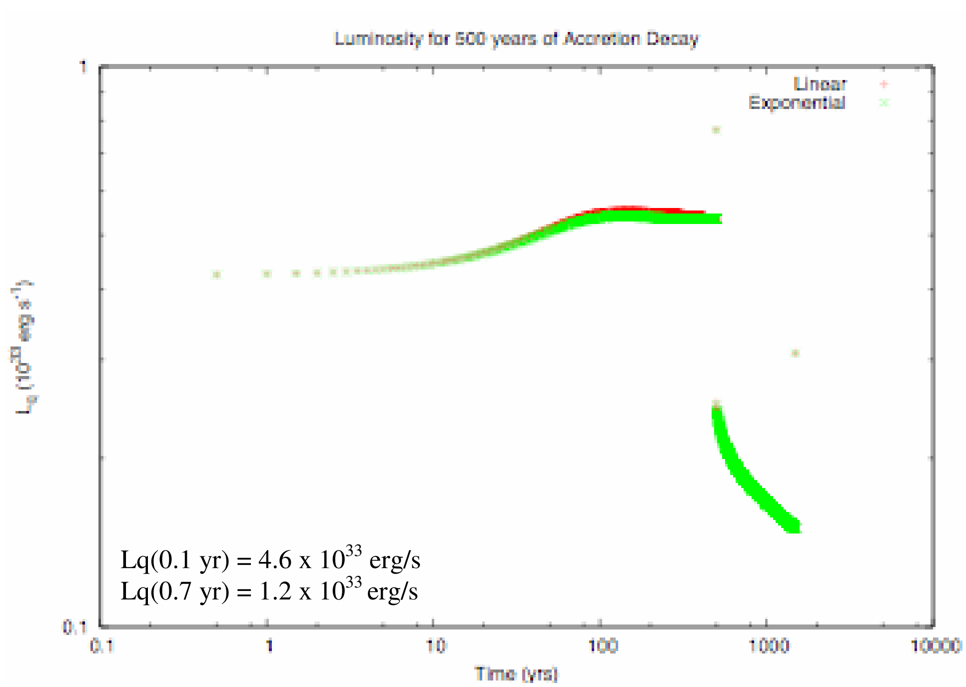

Figure 4. Luminosity of neutron star for 500 yrs of accretion decay. The luminosity increases as the accretion decay gets lower for both the linear and exponential model.

As shown in Figure 5, the quiescent luminosity of a neutron star that has a very long accretion decay length is consistently higher than other models and does not change much. The exponential and linear models are similar in shape and luminosity, though the linear model is slightly higher then the exponential. The luminosity level is about twice what it would be if the accretion was completely off for the same periods of time.

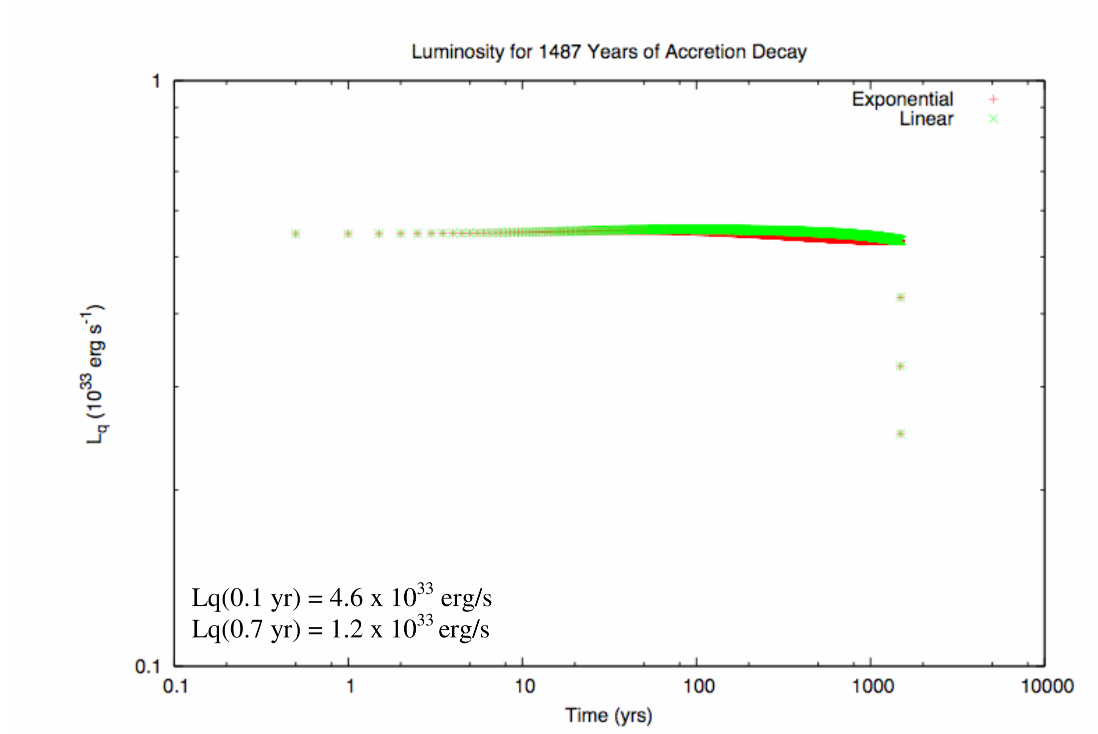

Figure 5. Luminosity of neutron star for 12 yrs of accretion, 1487 yrs of accretion decay and 1 yr off.

Figure 6 compares the luminosity level for all the different accretion decay lengths. When there is no accretion decay the luminosity is lower than if there is even 12 yrs of accretion decay and even higher if there is 500 yrs of accretion decay. The luminosity lowers for all three models as time passes, but the longer the accretion decay length, the steeper the drop in luminosity towards the end of the cycle. The 1487 yrs of accretion decay was left out as it does have enough data points to accurately model the luminosity in quiescence. These data points are significantly higher than what the model predicts so they were left out.

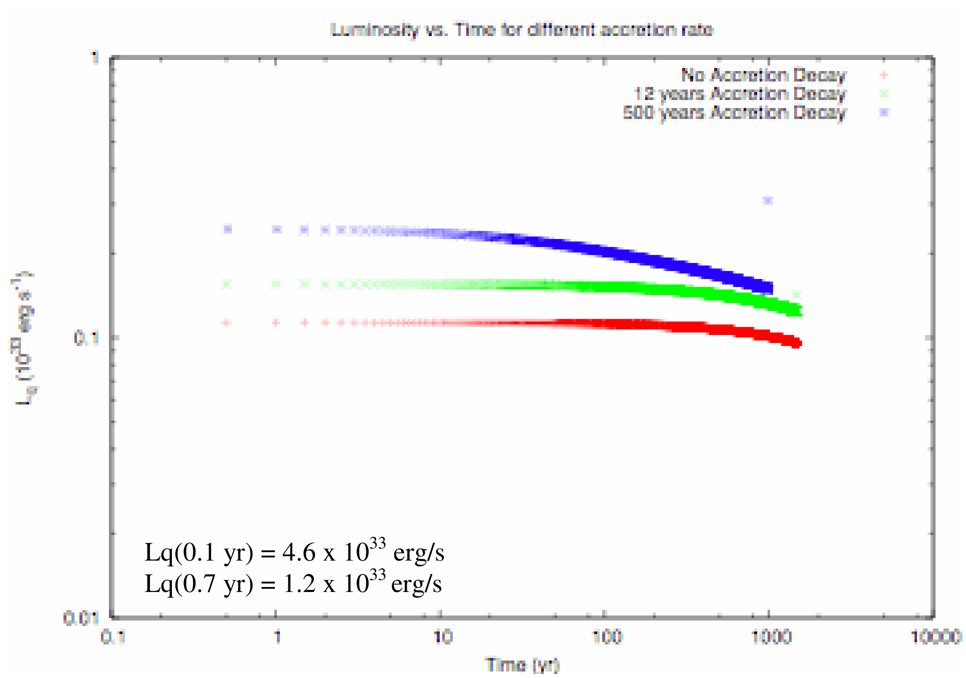

Figure 6. Luminosity of neutron star for different accretion decay lengths during quiescent interval using the linear model.

All of the previous graphs are for accretion decay length after the total outburst length of 12 yrs. For small periods of accretion decay length, there is a difference in luminosity levels in the quiescent period. The accretion rate may be decaying though the source may still be observed in outburst. It is unlikely that the neutron star accretes material at the same rate throughout its outburst period. It may be that KS 1731-260 has reached its quiescent period within 12 yrs, which the decay length. To encompass this parameter, a simulation was run consisting of an outburst period of 6 yrs and a decay length of 6 yrs while having 1488 yrs of quiescence. The luminosity in Figure 7 is lower than the observed values and the shape of the graph is similar to Figure 2. However, the values for the luminosity in the quiescence period are below what they were in Figure 2. This would imply that another model needs to be used for more accurate results.

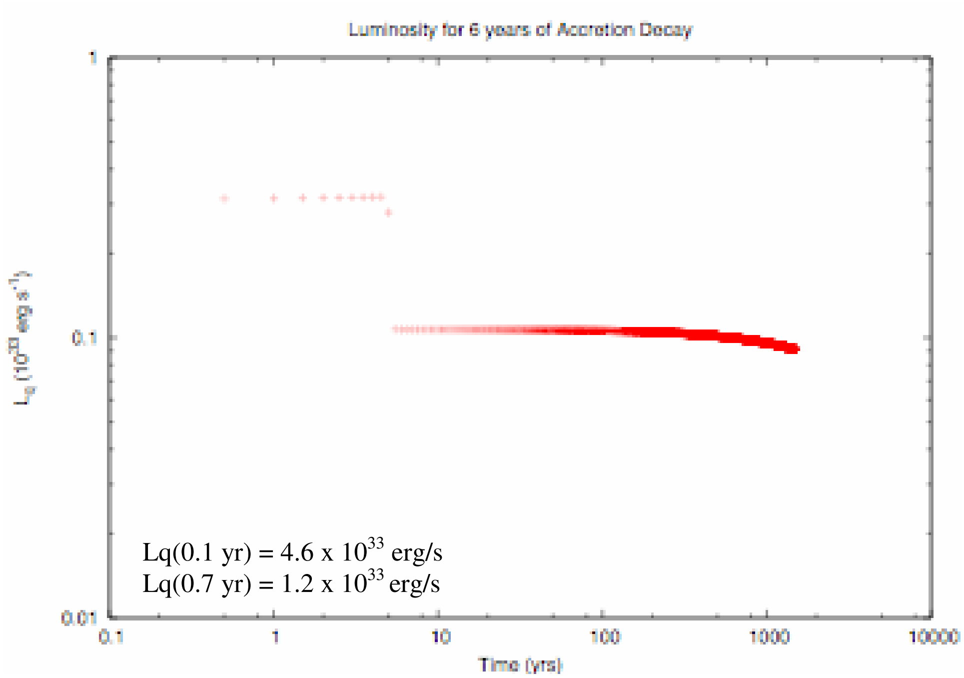

Figure 7. Luminosity of neutron star assuming outburst period of 6 yrs and 6 yrs accretion decay length.

Conclusion

This senior project is based on a previous model of transients in LMXB systems. The assumption that a star does not immediately stop accreting material but does so at a steady rate was taken into account. It is unlikely that a star would have the same accretion rate throughout its outburst period. The luminosity of a neutron star during its quiescent period is higher if a higher accretion decay length is used. The lowest luminosity was for the model where the accretion shuts off instantly. To see the difference between different modes of accretion decay, exponential and linear models were considered. The results shows there is not much difference in the luminosity of the neutron star if a linear accretion decay length is used compared to an exponential decay length. Compared to the well known neutron star KS 1731-260, the observations do not match with the luminosity that is predicted by the model. This simulation was run using only the enhanced neutrino emission and high conductivity crust. Future work could focus on combining enhanced and standard neutrino emission with high conductivity and low conductivity crust to see if the observations match to the data more precisely.

Bibliography

[1] E. F. Brown. *ApJ,* 531:988, 2000.

[2] E. Brown and M. Ouellette. *APHA,* 25:163, 2006

[3] R. Freedman and W. Kaufmann. *Universe.* W.H Freeman and Company, New York, 2007.

[4] J. Lattimer and M. Prakash. *Science*. 304:5670, 2004

[5] M. O'Brien and S. Kawaler. *APJ*, 539:372, 2000

[6] M. Ouellette. *Heating and Cooling of Neutron Star Crust.* Michigan State University, 2005.

[7] D. Psaltis. arXiv:*apj*/0410536v1, 2004.

[8] R. Rutledge et al. *ApJ*, 514:945, 1999.

[9] R. Rutledge et al. *ApJ*, 580:413. 2002

[10] D. T. Wickramasinghe et al. *J. Phys.: Conf. Ser.* **172** 012037, 2009

[11] R. Wijnands et al. *ApJ*, 573:L45, 2001.