A search for near-infrared variability from the ultraluminous X-ray pulsar M82 X-2

INTERNSHIP PROJECT

Alba Rodríguez Castellano

Tutor:
Dr. Marianne Heida, ESO

Co-tutors:
Dr. Matteo Bachetti, INAF Cagliari
Dr. Tom Maccarone, Texas Tech

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1. Introduction

Ultra-luminous X-ray sources (ULXS) are off-nuclear point-like sources with luminosities that are comparable to or above the Eddington luminosity of stellar black holes [5], that is, 10^{39}–10^{42} erg s^{-1}. During this project we analyzed Keck NIRC2 data from the ULX pulsar (ULXP) M82 X-2 discovered by Matteo Bachetti [1]. The main goal of this analysis was to shed some light into the position of M82 X-2 and the characteristics of its donor star. Several attempts (theoreticals and observationals) have been made in previous papers [4] [3] but the nature of this star has not yet been confirmed. It is only known with certainty that there is a lower limit on the mass of 5 $M_\odot$ [2] and that it might be turning off the main sequence. Also, the position from X-rays is known to an accuracy of $\sim$ 1 arcsecond what we tried to improve in NIR to no avail. All the notebooks and scripts which have been used in this work can be found at the GitHub repository `https://github.com/albarc3/M82_ESO`.

2. Data preparation

In this section, we will describe the process followed to prepare Keck NIRC2 data. All these data were downloaded via the Keck science archive with Tendulkar as principal investigator. Furthermore, we selected the option extracted/calibrated data so during the project we used these pipeline calibrated data as we only wanted to see first if we could find something notable. Thus, in total we downloaded 96 science files from which 44 are from filter Kp, 24 from filter H and 28 from filter J.

2.1. Aligning the images

The first step in the process was to correctly register the images per filter. For this purpose, we used the Python package *Astroalign* that has a function that automatically align the images that are given as the input.

Due to some defects in the images (mostly blurry images) and that others were taken in a wider field to see the tip-tilt "star", we finally end up with the following images per filter:

- Filter Kp $\longrightarrow$ 32 images (25 from the 1st night and 7 from the second night)
- Filter H $\longrightarrow$ 24 images
- Filter J $\longrightarrow$ 22 images

Also, in this step all the images were background subtracted using the median obtained via the sigma-clipped statistics of the images. This is already implemented in the *astropy* function **sigma_clipped_stats** and returns not only the median but the mean and standard deviation.

2.2. Combining the images

Secondly, we combined the registered images per filter to create a MASTER science image. In this case, we used the packages *ccdproc* and *Astropy*. In the case of filter Kp we separated as well the combined images per night of observation, that is, DATE-OBS = 2015-01-31 for the first night and DATE-OBS = 2015-02-04 for the second one.

The approach that we used to combine the images is the following. First, we excluded the extreme values using sigma clipping, with the median as the typical value and the MAD estimator of the standard deviation. Then we averaged the remaining pixels across all of the images as suggested in Matt Craig's CCD Data Reduction Guide. Finally, we subtracted the background of the combined image using the same process that was described in Subsection 2.1

3. PSF calculation

As Keck doesn't have any already-built PSF available it was also necessary to build our own. To accomplish this task we used Phoutils package and in particular the **EPSFBuilder** function to build the effective PSF (ePSF). The ePSF is an empirical model describing what fraction of a star's light will land in a particular pixel.

Thus, we built the corresponding ePSFs for each image using the same reference stars (see Figure 1) selected by checking their brightness profile with the DS9 **Projection** option. Then we extracted the data of the stars from the image using **extract_stars** as 80×80 pixels boxes[1]. The **extract_stars** function requires the input data as an NDData object. The key distinction from raw numpy.ndarray is the presence of additional metadata such as uncertainty, mask, unit, a coordinate system and/or a dictionary containing further meta information.

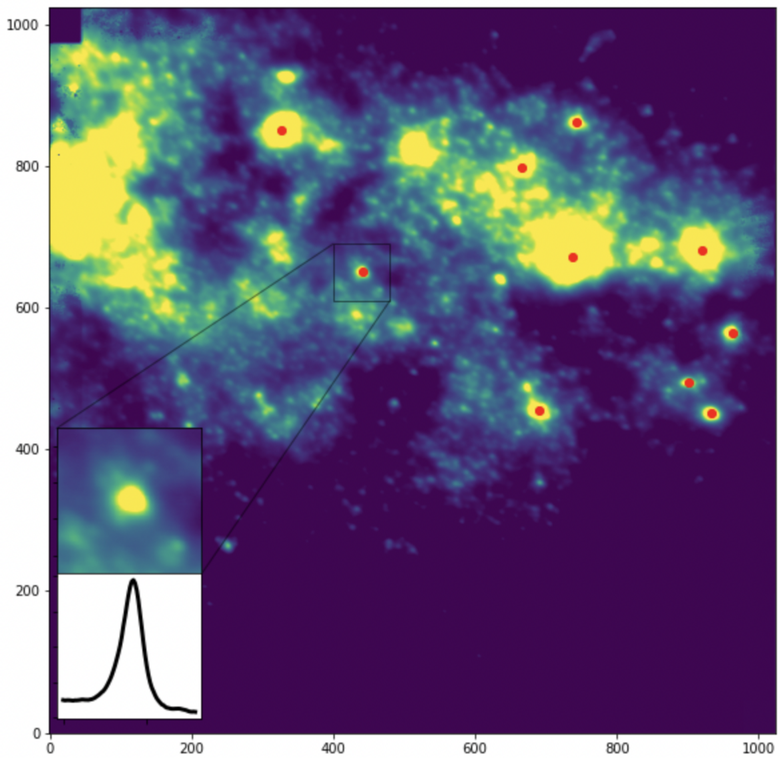


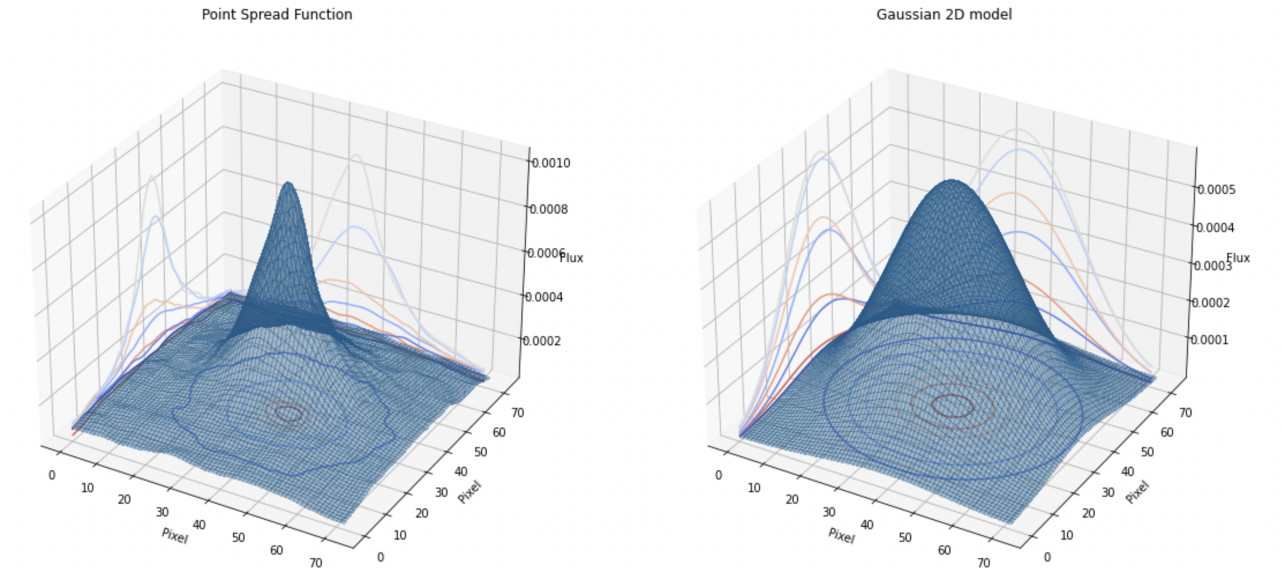
Figure 1: M82 combined image for filter K in false color where the reference stars selected to built the ePSF are indicated by a red dot. A zoom in region of one of the stars is also shown together with its brightness profile.

[1]This size is small enough to contain the minimum contamination of other sources and big enough to not be pixelated

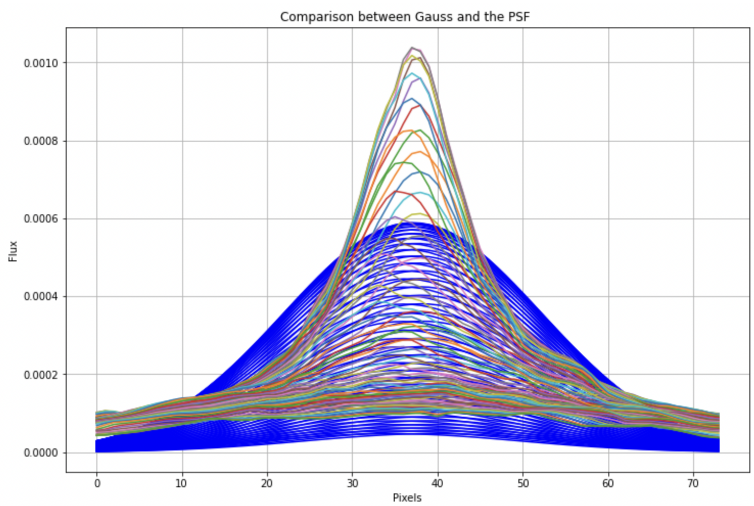
After extracting the stars, we used them to build the EPSF with the parameters oversampling = 1 and max-iters = 1. Also, it should be noted that if any of these parameters are incremented the ePSF begin to have a nonsense/pixelated shape (at least using these data). The latter have been pointed out in some open issues at *Phoutils* GitHub repository.

Finally, we fitted all the normalized ePSFs to a Gaussian 2D model. However, as we are at adaptive optics (AO) photometry case, the ePSFs structure, with a core dominated by the AO residual and seeing-limited wings, is not accurately modeled by classical functions and it would be necessary to fit it not only with a Gaussian 2D model but also with a Lorentzian 2D model that could fit the wings of the distribution (a model that is not implemented in *Astropy* nowadays). Furthermore, as this is a very crowded field it is very difficult to completely isolate stars and in most of the cases there will be some contamination.

The construction of ePSFs was automatized via a .py script available in the repository cited in the introduction. To run it, it's only necessary to write in the terminal > **ipython name-of-script.py** in the correct directory. There are two .py files for each filter, PSF_x.py is where the function to be used is defined whereas PSFx_loop.py runs the function for every image (you will have to update the directories). Also, all the images are trimmed to get rid of the black spaces around the PSF using the script Trim.py.



(a)



(b)

Figure 2: (a) Left: Real 3D ePSF plot. Right: Gaussian 2D fit to the real ePSF 3D plot. (b) Superposition of the real PSF and the Gaussian 2D fitting projections.

4. Zero point calibration using HST data

In order to correctly determine the sources' magnitudes, first we needed to calculate the zero point of the system. As we lack information about any known/tip-tilt star's tabulated magnitudes, we had to use HST F110W and F160W data to attempt to calibrate our Keck H and J data. Unfortunately, the data from filter K couldn't be calibrated because there is neither HST nor ground-based data available with a resolution high enough to detect the sources.

Thus, we chose 10 different stars (see Figure 3) that Marianne Heida had calibrated before in order to estimate the zero point. To do this, we used PSF photometry because is more accurate than aperture photometry in this field. In particular, the function that we used is **BasicPSFPhotometry** from *Phoutils* with the positions fixed in the stars' coordinates. As inputs we had to define the **bkg_estimator** that we calculated via the function **MMMBackground()**; **group_maker** where we used the **DAOGroup**(fwhm); **psf_model** in which we introduced the data from the PSF that we had built before using the **EPSFModel()** function; **fitter** as **LevMarLSQFitter()** and **fitshape** as the size that the selected stars occupy in the image.

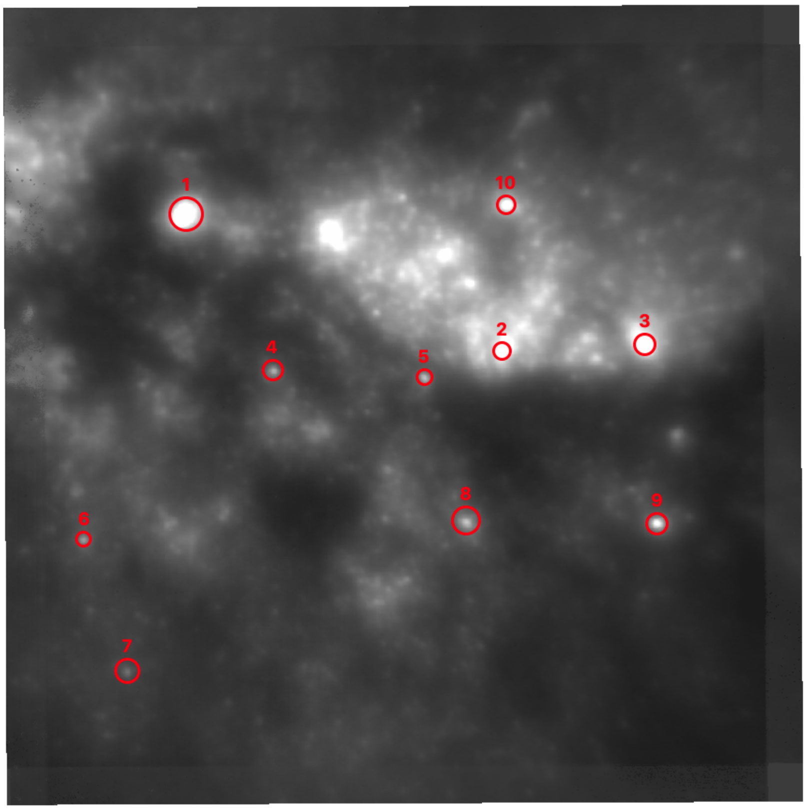


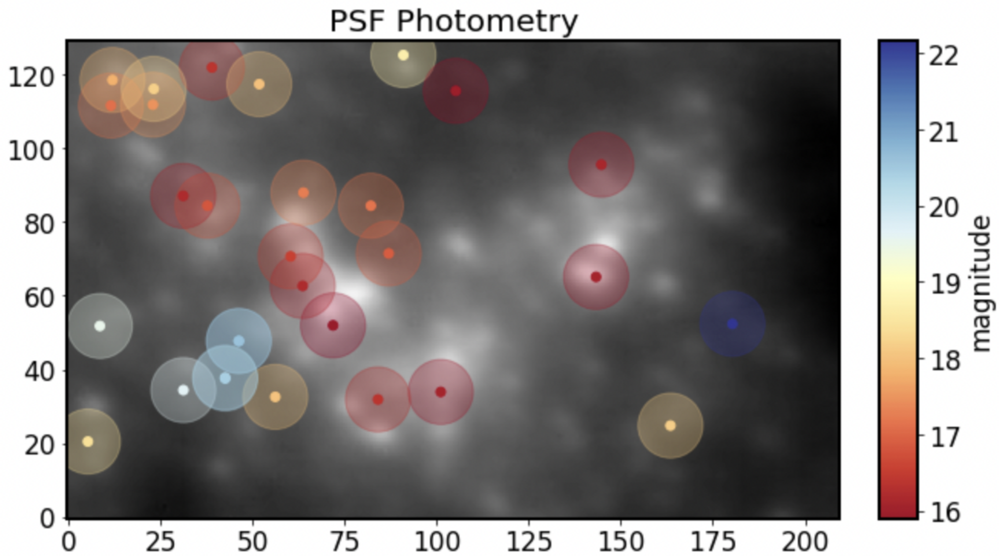
Figure 3: Selected stars

Then, we calculated the magnitudes through Equation 1 since **BasicPSFPhotometry** only gives us fluxes. In this way, the zero point is the difference between Marianne's HST calibrated magnitudes and the ones that were measured in the new Keck images.

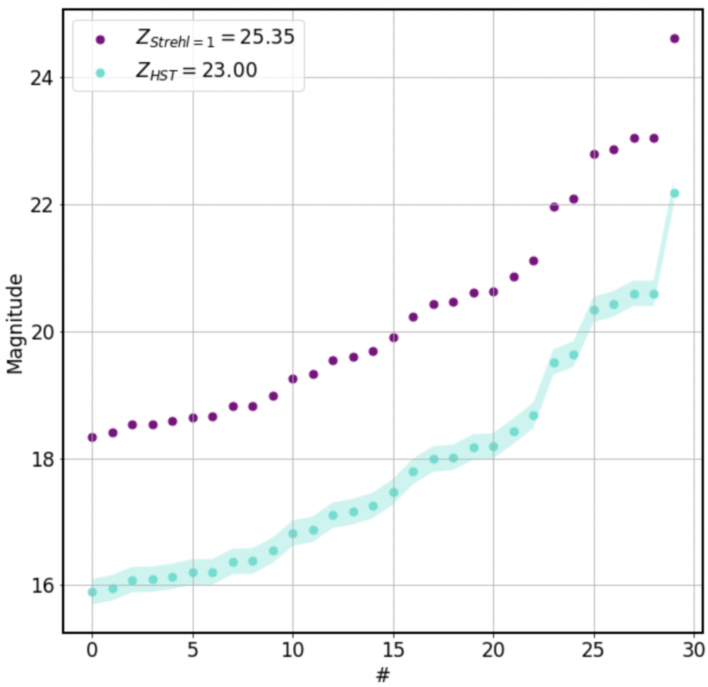
$$m = -2.5 \log(F/t_{\rm exp}) \ ; \ t_{\rm exp} = 60 \text{ s} \tag{1}$$

5. Flux calibration

With the zero points already calculated, we applied PSF photometry to M82 X-2 region in Keck's images but in this case using **DAOPhotPSFPhotometry()**. This time the inputs were **crit_separation** which value has to be integer multiples of the PSF's Gaussian fit fwhm ; **threshold** which we set as 1.5σ; **fwhm** which is the one from the Gaussian fit of the PSF; **psf_model** that we defined as **EPSFModel()** of our PSF data; **fitter** again as **LevMarLSQFitter()**; **fitshape** as the size that the selected stars occupy in the image and **niters** as the desired number of iterations. Thus, using Equation 1 again but modified by the zero point constant, we determined an estimation of the magnitudes of the field.



(a)



(b)

Figure 4: Examples for filter H (a) M82 X-2 region with the positions of the stars detected indicated as colored circles scaled according to their magnitudes (b) Difference between HST calibrated magnitudes and the ones according to Strehl=1.

6. Image subtraction

After having completed the previous steps, we were able to perform the images subtraction using **PyZOGY**. To correctly compute it, we need to set as input a reference image and its normalized PSF as well as a "science" image and its normalized PSF. In particular, for each filter, we chose as reference image the corresponding combined image.

In order to compute the subtraction automatically, we also wrote a subtractionX.py script that calculates and saves in the indicated directory the subtracted images in a .FITS format and also a .png containing the *mat-*

plotlib colorscaled plot.

As a special case, we split the K data into the two different nights and we subtracted one from the other. This is because it's the only filter where we have data from 2 nights and we thought that we might see something interesting.

However, after all the different trials we didn't find any evidence of M82 X-2 in any of the images and even in the images that we cropped in DS9 to avoid extreme values. The only thing that could be seen is a pattern of brighter points that are due to bad pixels and not well subtracted bright stars. Possibly this can be improved with a better calculation of the ePSF using a 2D background subtraction since this is a very crowded region.

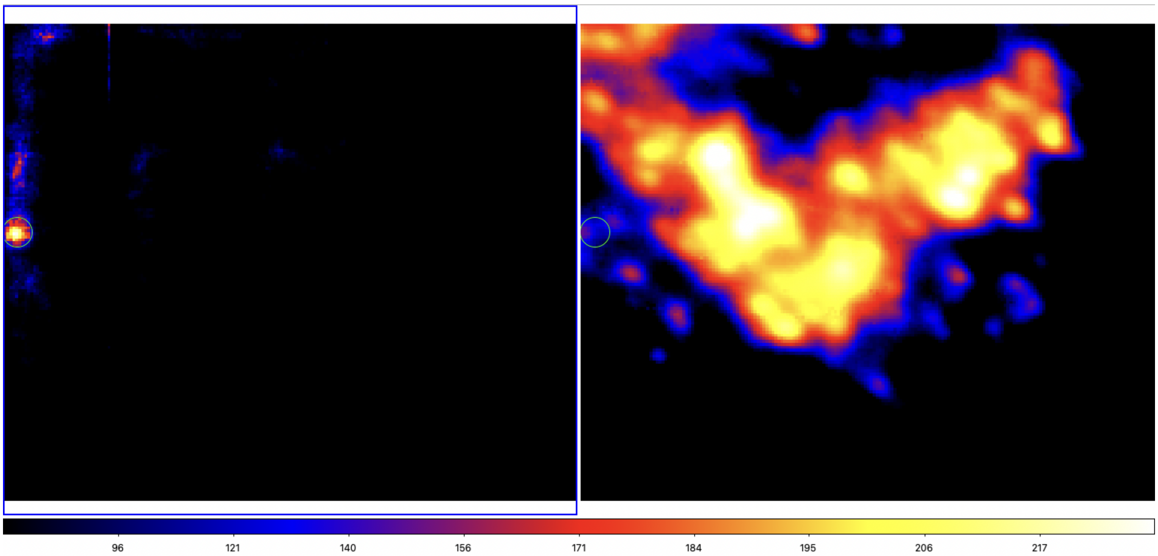


Figure 5: Filter K images. Left: Subtracted image as the result of the first night's combined image minus the second night's combined image. Right: First night's combined image.

7. MIST isochrones to estimate the magnitude of the donor star

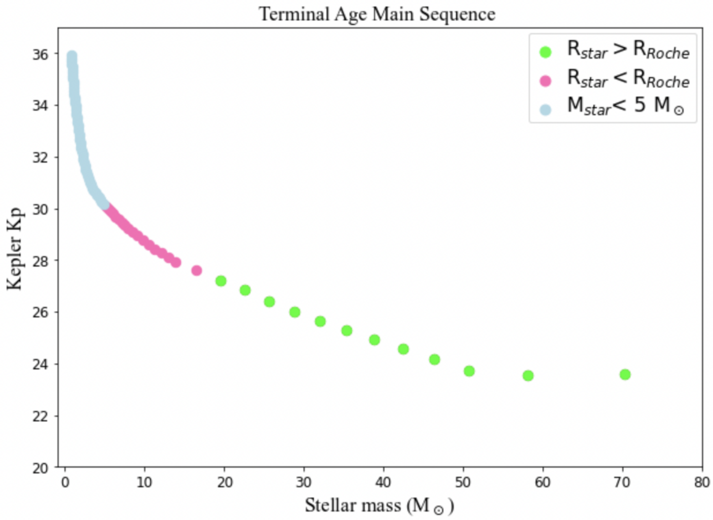
Finally, knowing that the donor star of the system must be turning the main sequence (MS) we estimated the magnitude that it has to have depending on the mass. To compute these values we used MIST's Isochrones Web Interpolator with the following parameters:

- **Rotation:** $v/v_{crit} = 0$
- **Age:** MIST standard age grid
- **Composition** [Fe/H]= - 0.3
- **Synthetic Photometry:** UBV(RI)c, 2MASS, Kepler, Hipparcos, Gaia (Vega) / JWST
- **Extinction (Av):** 5

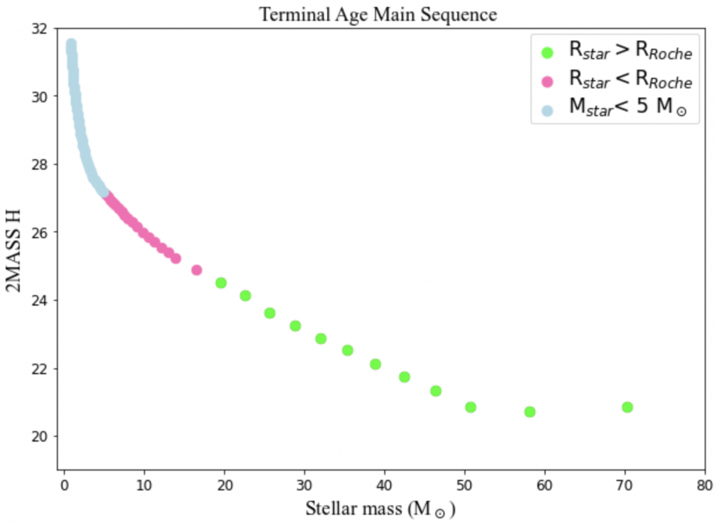
Then, we uploaded the .iso.cmd file into Python as well as the read_mist_model.py script necessary to read that data. Furthermore, as we have said that the star is ending its life in the MS, as a first estimation we only considered stars at the Terminal Stage Main Sequence (TAMS) (EEP = 454). One thing to bear in mind is that the magnitudes that are given are the absolute ones, so to calculate the apparent ones for M82 X-2 [4]

$$m = M + 27.74 \tag{2}$$

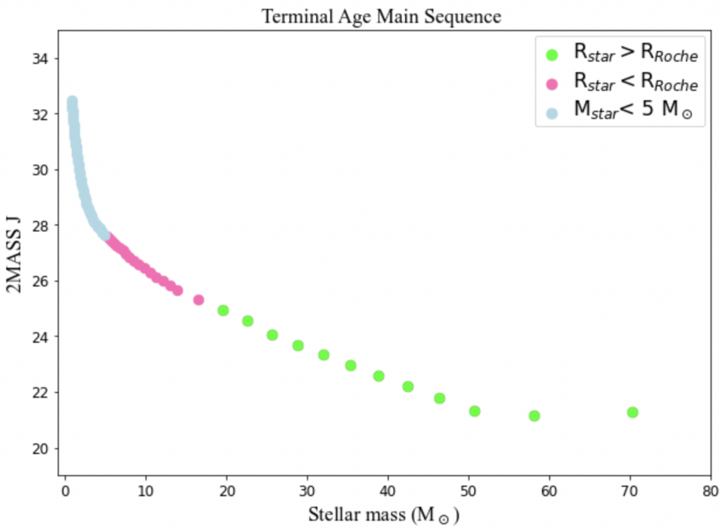
As an additional parameter, we calculated the Roche Lobe radius of the donor star for a neutron star of 1.4 $M_\odot$ and an orbital period of 2.5 days [1]. Thus, we excluded also the stars whose radius were below its Roche Lobe radius.



(a)



(b)



(c)

Figure 6: Stellar mass ($M_\odot$) versus the apparent magnitude for filters a) Kepler Kp b) 2MASS H c) 2MASS J. In light blue are represented the stars that have a mass below than 5 $M_\odot$ that is the donor stars' lower limit [1], in pink are represented the stars whose radius are below the Roche Lobe radius and in green the stars whose radius is above the Roche Lobe radius.

8. Conclusions

In despite of having obtained with Keck/NIRC2 a better resolution than the previous HST images of the field, we couldn't shed light into the exact position of M82 X-2. This is, partly, due to the lack of a variable source evidence in the subtracted images. Furthermore, we may need to use other filters to detect the source as its magnitude might be so low for the ones used in this case with Keck. For example, the lowest magnitude that we could detect in the X-ray M82 X-2 compatible region is 22 but a great amount of candidates are below this value.

On the other hand, we were also limited in terms of the amount of data since there are only 2 nights available with an exposition time of 60 seconds for each image (30 min per filter approximately). Moreover, as we explained is Section 4 there wasn't any reference star to correctly calibrate the images. So, for future observations might be a good option to observe M82 X-2 for a longer time and select beforehand reference stars on the field.

Lastly, as we also explained in Section 3, the region is very crowded and spatially variable so the PSF possibly could be highly improved via a 2D background subtraction of the image. Also, since it is NIRC2 uses an adaptive optics system the calculation of a good PSF is harder and also its modeling (we have to add a Lorentzian component to the usual Gaussian one). We highlight the importance of building a good PSF in order to have reasonable results.

References

[1] Matteo Bachetti, FA Harrison, Dominic J Walton, BW Grefenstette, D Chakrabarty, F Fürst, Didier Barret, A Beloborodov, SE Boggs, Finn Erland Christensen, et al. An ultraluminous x-ray source powered by an accreting neutron star. *Nature*, 514(7521):202–204, 2014.

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[3] Matteo Bachetti, Thomas J Maccarone, Murray Brightman, McKinley C Brumback, Felix Fürst, Fiona A Harrison, Marianne Heida, Gian Luca Israel, Matthew J Middleton, John A Tomsick, et al. All at once: Transient pulsations, spin-down, and a glitch from the pulsating ultraluminous x-ray source m82 x-2. *The Astrophysical Journal*, 891(1):44, 2020.

[4] M Heida, FA Harrison, M Brightman, F Fürst, D Stern, and DJ Walton. Searching for the donor stars of ulx pulsars. *The Astrophysical Journal*, 871(2):231, 2019.

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