AST 381: Planetary Astrophysics: Homework #2

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Code, images, and text files can be found at `https://github.com/raquizzi/ast381_hw2`.

Part 1: Go to the Keck website and search for observations of ROXs 42B and ROXs 12 with the NIRC2 camera (the facility adaptive optics imager).

- Downloaded 27 calibrated images of ROXs 12 and 46 calibrated images of ROXs 42B.

Part 2: Write a code in your language of choice that, for each image, will measure the x/y pixel position of the star underneath the coronagraph, and write the file name and x/y coordinates to a text file. Those x/y coordinates will be useful in subsequent steps when "registering" images.

- Wrote program ("part2.pro") that looks for the calibrated images of each object in their respective folders and finds the centroid based on a guess. The initial guess came from me looking at the image and estimating the central pixel placement of the coronagraph.
- IDL's cntrd.pro was unable to find a centroid for one of ROXs 42B's images (N2.20110623.33576_drp.fits). I chose not to use this image for the rest of the assignment.

Part 3: Write a code that, for all images of a star, will "register" them (shift them all so that the star is at the same x/y position in them) and then produce output images with the sum and the median of each stack. It's fine to call an outside routine to do the actual shift, such as the IDL routine fshift. Note that since the sky is rotating, this has the effect of creating an average representation of the point spread function while simultaneously blurring any companions in the tangential direction. Produce sum and median images for both stars.

- Wrote program (register.pro) that "registers" each image.
- The program takes 3 inputs: an image data cube of all of the images for the object, an array of the object's centroid x-coordinates from these images, and an array of the object's centroid y-coordinates.
- The program outputs an image data cube of the registered images.
- Using IDL's sum and median routines, "p3sum.fits" and "p3med.fits" files were created for each object with their registered images (See Figures 1 through 4).

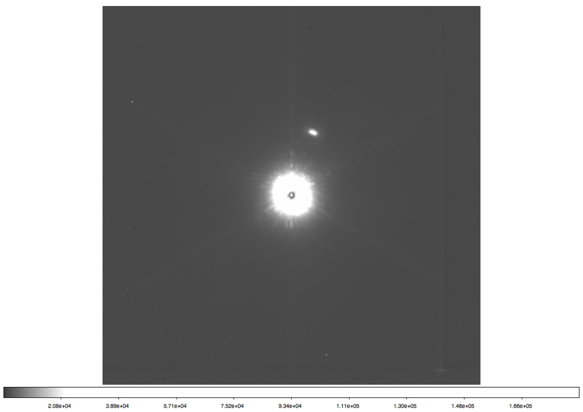

Figure 1: Sum image of registered ROXs 12 images. Stretch is linear and min-max.

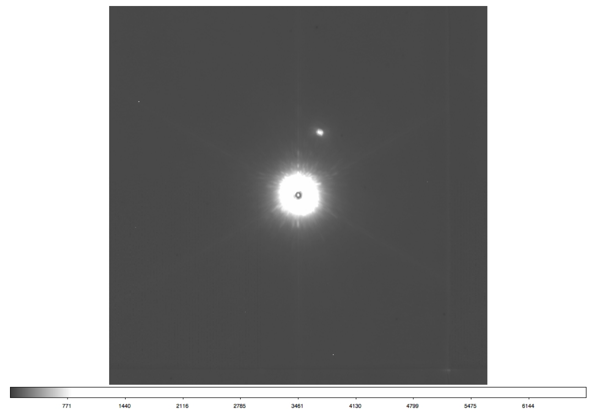

Figure 2: Median image of registered ROXs 12 images. Stretch is linear and min-max.

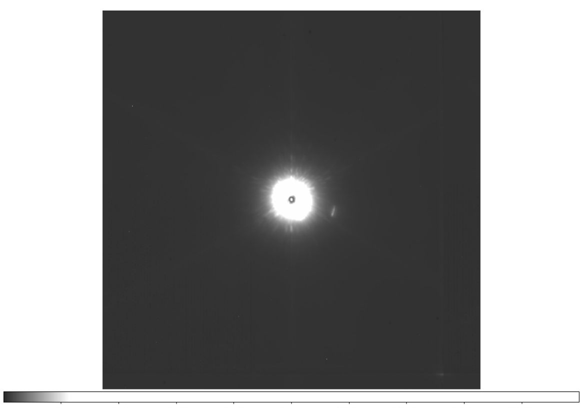

Figure 3: Sum image of registered ROXs 42B images. Stretch is linear and min-max.

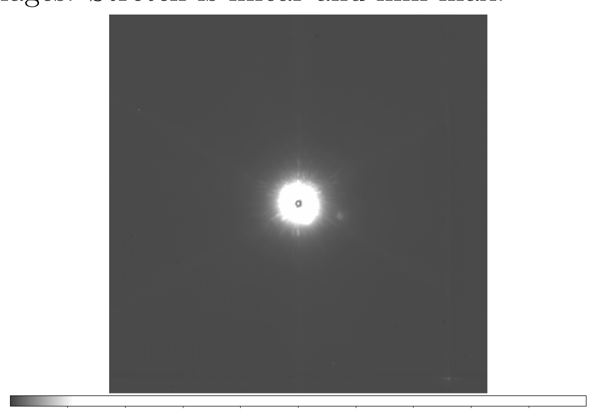

Figure 4: Median image of registered ROXs 42B images. Stretch is linear and min-max.

Part 4: Write a modified version of the last code that, while stacking the images, will rotate each individual image around the position of the primary star so that north is up. It's fine to use outside code for doing the rotation, such as the IDL routine rot. This has the effect of causing the flux of real companions to add up, while the stellar PSF blurs tangentially. Again, produce sum and median images for both stars. Note that you can get the PA of the +y axis from the FITS headers, using a combination of parameters: PA = PARANG + ROTPPOSN - EL - INSTANGL

- Wrote program (register_rot.pro) that "registers" each image to the center, then rotates it so that North is parallel to the y-axis.
- The program takes 4 inputs: an image data cube of all of the images for the object, an array of the object's centroid x-coordinates from these images, an array of the object's centroid y-coordinates, and an array of the images' +y-axis position angles.
- The program outputs an image data cube of the registered and rotated images.
- Using IDL's sum and median routines, "p4sum.fits" and "p4med.fits" files were created for each object with their registered and rotated images (See median images in Figures 5 and 6).

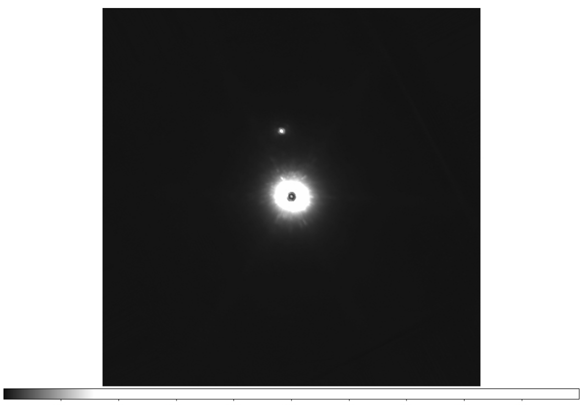

Figure 5: Median image of registered and rotated ROXs 12 images. Stretch is linear and min-max.

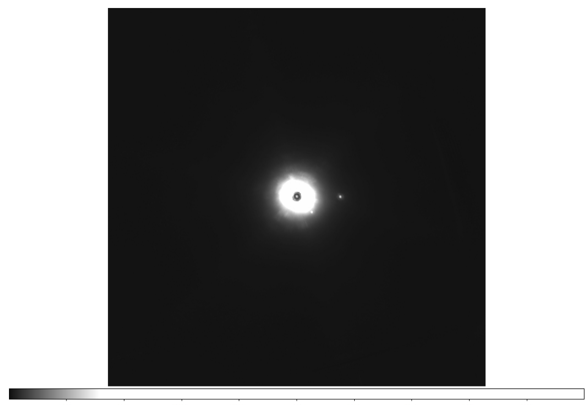

Figure 6: Median image of registered and rotated ROXs 42B images. Stretch is linear and min-max.

Part 5: Write a code that, for each image, calculates the brightness profile as a function of distance away from the star (that is, calculates the azimuthal median in concentric rings) and subtracts it off of that image. If you want to game through the best way to do this, stop by and we can chat. Do that for each individual image, and then use your code from steps 3 and 4 to produce corresponding stacked sum and median images.

- Wrote program (ann_az_med.pro) that creates a brightness profile for each image in a data cube. I then called this function in hw2.pro to create an array of images that had this azimuthal median subtracted off, and passed this through register_rot.pro
- The ann_az_med.pro program takes 2 inputs: an image data cube of all of the registered images for the object, and and annulus width.
- The program outputs a data cube of brightness profiles for each image. This was then subtracted from the output from Part 3, then rotated using register_rot.pro.
- Using IDL's sum and median routines, "p5sum.fits" and "p5med.fits" files were created for each object with their registered and rotated images (See Figures 7 through 8).

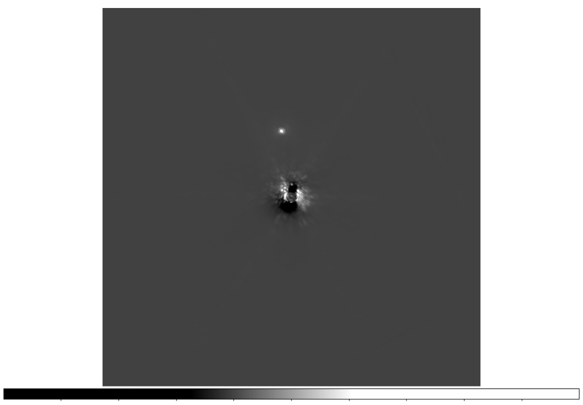

Figure 7: Median image of azimuthal median subtracted ROXs 12 images. Stretch is linear and min-max.

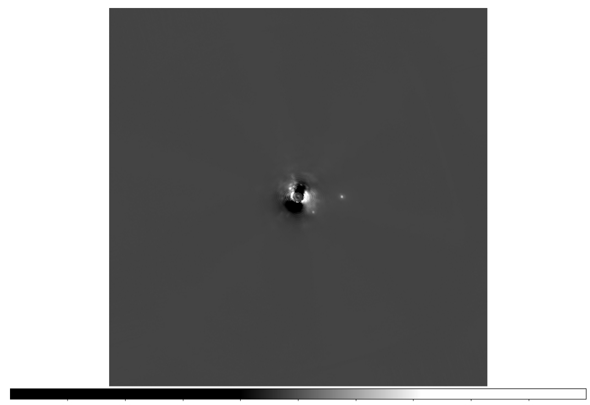

Figure 8: Median image of azimuthal median subtracted ROXs 42B images. Stretch is linear and min-max.

Part 6: Write a code that, for each image, subtracts off the median-combined image of the PSF (from Part 3). This is the classical definition of "angular differential imaging." After producing these ADI-subtracted images, register and stack them (via sum and median) as in Part 4.

- Within hw2.pro I found the part of a 1024×1024 array that was at least 18 pixels but no more than 68 pixels away from its center. This was the "broad ring" away from the science target used to scale the median PSF to each science image produced in Part 3.
- A new image array "img_adi" was created that passed the median-subtracted images through register_rot.pro
- Using IDL's sum and median routines, "p6sum.fits" and "p6med.fits" files were created for each object with their registered and rotated images (Median images are shown in Figures 9 through 10).

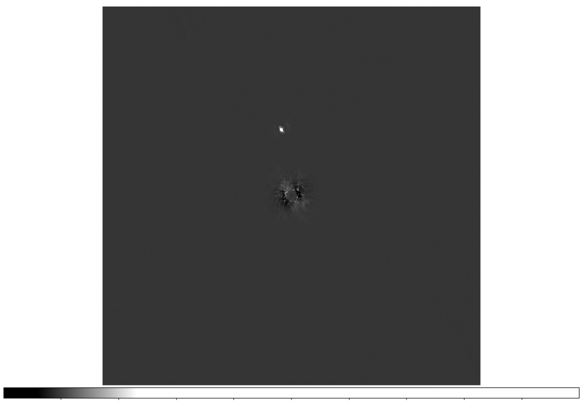

Figure 9: Median image of Part 3 images less their median PSF for ROXs 12. Stretch is linear and min/max.

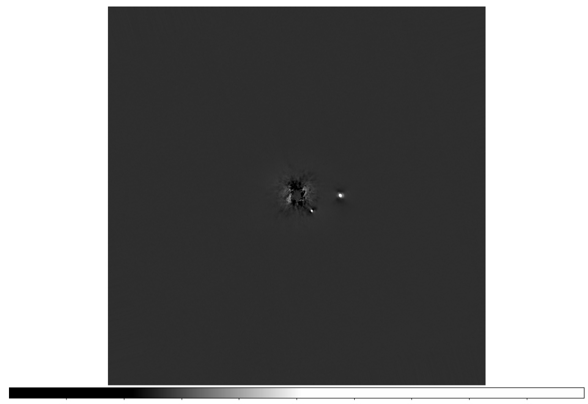

Figure 10: Median image of Part 3 images less their median PSF for ROXs 42B. Stretch is linear and min/max.

Part 7: Write code that, for each image of a given star, compares it to all the images of the other star and finds the one that has the most similar PSF, then subtracts that calibrator image off. (I suggest that you output the name of that best-matching image to a text file, to allow for ease of grading.) After producing these best-PSF-subtracted images, register and stack them (via sum and median) as in Part 4.

- Within hw2.pro, I found the part of a 1024×1024 array that was at least 18 pixels but no more than 68 pixels away from its center. This was the “broad ring” away from the science target used to scale each science image produced in Part 3 to one another.
- Within in hw2.pro, I also created an array of χ^2 values to keep track of the residuals. The diagonal elements of this array needed to be set to a very high value to ensure the best-fit-PSF was not its own science image.
- A new image array “img_psf” was created that passed the best-fit-PSF-subtracted images through register_rot.pro
- Using IDL’s sum and median routines, “p7sum.fits” and “p7med.fits” files were created for each object with their registered and rotated images (Median images are shown in Figures 11 through 12).
- The best-fit-PSF science images are listed in Tables 1 and 2.

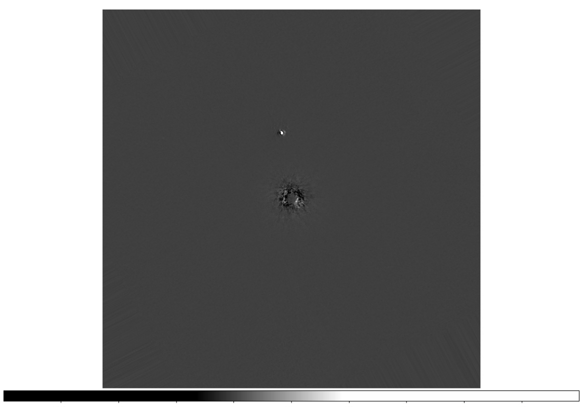

Figure 11: Median image of Part 3 science images less the best-fit-PSF from the other science images of ROXs 12. Stretch is linear and min/max.

Figure 12: Median image of Part 3 science images less the best-fit-PSF from the other science images of ROXs 42B. Stretch is linear and min/max.

Table 1: ROXs 12 Science Image Best-Fit-PSF Images

Filename	Best-Fit-PSF Filename
N2.20110623.36186_drp.fits	N2.20110623.36242_drp.fits
N2.20110623.36242_drp.fits	N2.20110623.36287_drp.fits
N2.20110623.36287_drp.fits	N2.20110623.36242_drp.fits
N2.20110623.36332_drp.fits	N2.20110623.36242_drp.fits
N2.20110623.36376_drp.fits	N2.20110623.36421_drp.fits
N2.20110623.36421_drp.fits	N2.20110623.36376_drp.fits
N2.20110623.36466_drp.fits	N2.20110623.36600_drp.fits
N2.20110623.36511_drp.fits	N2.20110623.36824_drp.fits
N2.20110623.36555_drp.fits	N2.20110623.36734_drp.fits
N2.20110623.36600_drp.fits	N2.20110623.36645_drp.fits
N2.20110623.36645_drp.fits	N2.20110623.36689_drp.fits
N2.20110623.36689_drp.fits	N2.20110623.36645_drp.fits
N2.20110623.36734_drp.fits	N2.20110623.36555_drp.fits
N2.20110623.36779_drp.fits	N2.20110623.36689_drp.fits
N2.20110623.36824_drp.fits	N2.20110623.36869_drp.fits
N2.20110623.36869_drp.fits	N2.20110623.36913_drp.fits
N2.20110623.36913_drp.fits	N2.20110623.36869_drp.fits
N2.20110623.36958_drp.fits	N2.20110623.37092_drp.fits
N2.20110623.37003_drp.fits	N2.20110623.36689_drp.fits
N2.20110623.37048_drp.fits	N2.20110623.37185_drp.fits
N2.20110623.37092_drp.fits	N2.20110623.36958_drp.fits
N2.20110623.37137_drp.fits	N2.20110623.36913_drp.fits
N2.20110623.37185_drp.fits	N2.20110623.37048_drp.fits
N2.20110623.37230_drp.fits	N2.20110623.37274_drp.fits
N2.20110623.37274_drp.fits	N2.20110623.37048_drp.fits
N2.20110623.37319_drp.fits	N2.20110623.37230_drp.fits
N2.20110623.37375_drp.fits	N2.20110623.37230_drp.fits

Table 2: ROXs 42B Science Image Best-Fit-PSF Images

Filename	Best-Fit-PSF Filename
N2.20110623.33237_drp.fits	N2.20110623.33349_drp.fits
N2.20110623.33349_drp.fits	N2.20110623.34492_drp.fits
N2.20110623.33441_drp.fits	N2.20110623.33491_drp.fits
N2.20110623.33491_drp.fits	N2.20110623.33441_drp.fits
N2.20110623.33690_drp.fits	N2.20110623.33237_drp.fits
N2.20110623.33782_drp.fits	N2.20110623.33876_drp.fits
N2.20110623.33876_drp.fits	N2.20110623.34089_drp.fits
N2.20110623.33938_drp.fits	N2.20110623.34291_drp.fits
N2.20110623.33988_drp.fits	N2.20110623.34392_drp.fits
N2.20110623.34039_drp.fits	N2.20110623.34089_drp.fits
N2.20110623.34089_drp.fits	N2.20110623.34139_drp.fits
N2.20110623.34139_drp.fits	N2.20110623.34089_drp.fits
N2.20110623.34190_drp.fits	N2.20110623.34849_drp.fits
N2.20110623.34241_drp.fits	N2.20110623.34492_drp.fits
N2.20110623.34291_drp.fits	N2.20110623.34598_drp.fits
N2.20110623.34341_drp.fits	N2.20110623.34392_drp.fits
N2.20110623.34392_drp.fits	N2.20110623.34341_drp.fits
N2.20110623.34442_drp.fits	N2.20110623.34598_drp.fits
N2.20110623.34492_drp.fits	N2.20110623.34241_drp.fits
N2.20110623.34543_drp.fits	N2.20110623.34849_drp.fits
N2.20110623.34598_drp.fits	N2.20110623.34291_drp.fits
N2.20110623.34648_drp.fits	N2.20110623.34543_drp.fits
N2.20110623.34698_drp.fits	N2.20110623.34748_drp.fits
N2.20110623.34748_drp.fits	N2.20110623.34698_drp.fits
N2.20110623.34799_drp.fits	N2.20110623.34492_drp.fits
N2.20110623.34849_drp.fits	N2.20110623.34190_drp.fits
N2.20110623.34900_drp.fits	N2.20110623.34748_drp.fits
N2.20110623.34980_drp.fits	N2.20110623.35687_drp.fits
N2.20110623.35031_drp.fits	N2.20110623.35132_drp.fits
N2.20110623.35081_drp.fits	N2.20110623.35485_drp.fits
N2.20110623.35132_drp.fits	N2.20110623.35182_drp.fits
N2.20110623.35182_drp.fits	N2.20110623.35132_drp.fits
N2.20110623.35233_drp.fits	N2.20110623.35283_drp.fits
N2.20110623.35283_drp.fits	N2.20110623.35233_drp.fits
N2.20110623.35334_drp.fits	N2.20110623.35384_drp.fits
N2.20110623.35384_drp.fits	N2.20110623.35586_drp.fits
N2.20110623.35435_drp.fits	N2.20110623.35636_drp.fits
N2.20110623.35485_drp.fits	N2.20110623.35536_drp.fits
N2.20110623.35536_drp.fits	N2.20110623.35636_drp.fits
N2.20110623.35586_drp.fits	N2.20110623.35233_drp.fits
N2.20110623.35636_drp.fits	N2.20110623.35536_drp.fits
N2.20110623.35687_drp.fits	N2.20110623.34980_drp.fits
N2.20110623.35739_drp.fits	N2.20110623.35879_drp.fits
N2.20110623.35828_drp.fits	N2.20110623.35879_drp.fits
N2.20110623.35879_drp.fits	N2.20110623.35828_drp.fits

Part 8: For each median image that you have produced in parts 4 through 7, pick out what appear to be the real objects and measure their positions in the same way as you did for the primary star. Using the pixel scale for NIRC2, which you can look up online or in the literature in various ways, measure the position angle and projected separation for each object. (For now, don't worry about distortion.)

- Used a pixel scale of 0.0009952 arcseconds per pixel (obtained from header of science images).
- Tables 3 through 5 list the centroid coordinates, projected separation (mas), and PA (degrees) for companions that appear to be real objects after the various processing techniques from Parts 4 through 7.

Table 3: ROXs 12b Centroid, Projected Separation, and PA from Median Images

Filename	X	Y	ρ (mas)	PA (deg)
p4med.fits	484.926	689.633	1788.22	8.66602
p5bmed.fits	484.926	689.633	1788.22	8.66599
p6med.fits	484.931	689.662	1788.50	8.66313
p7med.fits	486.286	690.018	1790.02	8.21919

Table 4: ROXs 42B b Centroid, Projected Separation, and PA from Median Images

Filename	X	Y	ρ (mas)	PA (deg)
p4med.fits	630.120	512.182	1175.53	270.088
p5bmed.fits	630.128	512.175	1175.61	270.082
p6med.fits	630.122	512.232	1175.55	270.112
p7med.fits	630.121	513.347	1175.62	270.653

Table 5: ROXs 42B c Centroid, Projected Separation, and PA from Median Images

Filename	X	Y	ρ (mas)	PA (deg)
p4med.fits	630.120	512.182	573.028	224.619
p5bmed.fits	630.128	512.175	577.833	224.595
p6med.fits	630.122	512.232	580.291	224.536
p7med.fits	630.121	513.347	578.780	225.719