Identification of Young Stellar Objects in NGC 7538 using Spitzer archive data

PAVAN VYNATHEYA
BS-MS STUDENT
IISER KOLKATA

Supervisor:
DR. SAURABH SHARMA
SCIENTIST 'D'
ARIES NAINITAL

1 INTRODUCTION

1.1 STAR FORMATION

Star formation is the process in which dense regions of molecular clouds condense into protostars. Molecular clouds are relatively dense regions of interstellar matter made up mostly of hydrogen, present in its molecular form.

Molecular clouds can vary vastly in size. The smallest ones are called Bok Globules, whose masses are less than a few hundred Solar masses. The largest ones, Giant Molecular Clouds (GMCs) have masses of about 10^5 Solar Masses and are spread across hundreds of light years. Their temperatures range around 10-20 K.

The fundamental requirement for star formation is that the 'inward' gravitational force (potential energy) must exceed the 'outward' gas pressure (kinetic energy). The virial theorem states that for hydrostatic equilibrium (of a molecular cloud), the potential energy must be twice that of the kinetic energy. If the mass of a cloud exceeds the 'Jeans mass', it will undergo gravitational collapse. The Jeans instability criterion depends on the temperature and density of a cloud.

Molecular clouds break into clumps, which in turn collapse to form individual protostars. These clumps are denser parts of the cloud. This results in the formation of a cluster of stars, which may stay together or drift apart.

Star formation can also be 'triggered'. This can occur due to shockwaves from a nearby supernova explosion or galactic collision. Triggered formation can also occur in the vicinities of HII regions (consisting of ionized hydrogen rather than molecular hydrogen).

After the clump or the cloud collapses, a protostar is born, which further evolves into a star.

1.2 YOUNG STELLAR OBJECTS (YSOS)

YSOs denote the early phase of stellar evolution. There are two groups of YSOs – protostars and pre-main sequence (PMS) stars.

A Protostar is the first stage of stellar evolution. When a molecular clump starts collapsing, it is called a protostar. When this happens, it starts spinning to form a spherical clump. The outer material forms a envelope, which eventually becomes a circumstellar disc (site for planet formation). Initially, the clump is transparent to radiation. As the density increases, it becomes opaque. Escaping IR radiation is trapped, resulting in increase in pressure and temperature of the protostar. The protostar gains mass as more material is accreted from the envelope.

A protostar becomes a PMS star when it blows away its outer envelope and becomes optically visible. A PMS star generates heat by gravitational contraction, and not by hydrogen burning. The star continues to collapse until its pressure and temperature are high enough for hydrogen fusion. When this happens, it is said to be a main sequence star. A PMS star, thus, has a higher radius than a main sequence star of similar mass. It also has a circumstellar disc, which eventually gets dissipated by accretion and planet formation. This disc is responsible for emission in far IR.

A PMS star can either be a T Tauri star (less than 2 Solar masses) or a Herbig Ae/Be star (2-8 Solar masses). Stars with masses greater than 8 Solar masses contract too quickly to have a pre-main sequence stage; they are already main-sequence stars.

Based on the stage of evolution, YSOs are classified into different classes. The classification is done based on the Spectral Energy Distributions (SEDs) of the YSOs.

1.3 CLASSES OF YSOS

The SED is a plot of brightness (or flux density) vs. wavelength (or frequency) of light. Based on their SEDs, YSOs are classified into four classes (see *Fig 1.*) –

- ***Class 0* –** They are protostars that are extremely faint in optical and near IR regions, but are luminous in submillimeter wavelengths.
- ***Class I* –** They are embedded sources with circumstellar discs and envelopes, which peak in the mid-IR to far-IR regions and are optically invisible.
- ***Class II* –** They have significant circumstellar discs, strong emission lines and IR and optical luminosities.
- ***Class III* –** They don't have circumstellar discs and weak emission lines.

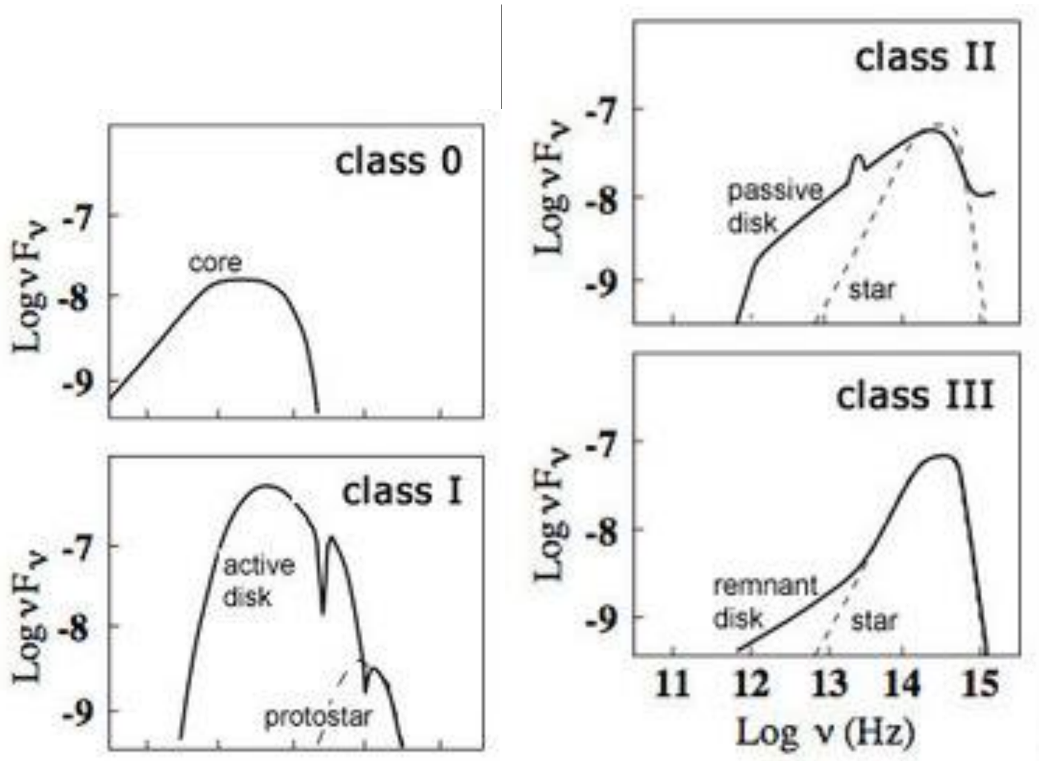


Fig 1: Typical SEDs of the various classes of YSOs (Flux density vs. frequency).

1.4 NGC 7538

NGC 7538 is an active Star Forming Region (SFR) in the constellation Cepheus, about 2.7 kpc from the Earth. Right Ascension and Declination of NGC 7538 are approximately 348.4° and 61.4°.

Since NGC 7538 is an SFR, it emits significantly in the infrared region of the EM spectrum. Thus, data from the Spitzer Space Telescope (SST), an infrared space telescope is used to gather this data.

1.5 SPITZER SPACE TELESCOPE (SST)

The SST is an infrared space telescope launched by NASA in 2003 as a part of the NASA 'Great Observatories' program. The other missions were the visible-light Hubble Space Telescope (HST), the Compton Gamma-Ray Observatory (CGRO) and the Chandra X-Ray Obserbatory (CXO).

The Spitzer carries three instruments on board –

- ***Infrared Array Camera (IRAC)* –** An infrared camera which operates simultaneously on four wavelength 'channels' – 3.6 µm, 4.5 µm, 5.8 µm and 8.0 µm. Each module uses a 256×256 pixel detector.
- ***Infrared Spectograph (IRS)* –** An infrared spectrometer with four sub-modules which operate at the wavelengths 5.3–14 µm (low resolution), 10–19.5 µm (high resolution), 14–40 µm (low resolution), and 19–37 µm (high resolution). Each module uses a 128×128 pixel detector.
- ***Multiband Imaging Photometer for Spitzer (MIPS)* –** Three detector arrays in the far IR – 128×128 pixels at 24 µm, 32×32 pixels at 70 µm, 20×20 pixels at 160 µm.

All Spitzer data is freely available online in the Spitzer Heritage Archive (SHA). Only IRAC data has be used in this project.

1.6 Two Micron All Sky Survey (2MASS)

The 2MASS was an infrared astronomical survey of the whole sky in the infrared spectrum which took place between 1997 and 2001. Two 1.3-m telescopes were used for the survey, one in Arizona, USA (Northern Hemisphere) and the other in Chile (Southern Hemisphere).

Observations were taken in three wavelength bands – J (1.235 μm), H (1.662 μm) and K (2.159 μm). The three channel cameras used 256×256 arrays. 2MASS data is available at the Infrared Science Archive (IRSA).

1.7 Image Reduction And Analysis Facility (IRAF)

IRAF is a software collection written at the National Optical Astronomical Observatory (NOAO) used primarily for data reduction and photometry. One specific package of IRAF used in this project is DAOPHOT.

DAOPHOT is a package for stellar photometry designed to deal with crowded fields. More details about this package (commands and parameters) are given in future sections.

1.8 Mosaicker And Point Source Extractor (MOPEX)

MOPEX is a software used for reducing and analyzing imaging data, and for creating mosaic images. MOPEX comes in two modes – Graphical User Interface (GUI) mode and Command Line mode.

In this project, MOPEX has been used in the Command Line mode. More details of the commands and various processes involved are given in future sections.

1.9 Python SED Fitter

The Spectral Energy Distribution (SED) fitter is a Python package used for fitting given data (YSO data) to their SEDs. It has various models which fit stars with data, in at least five wavelength bands, to the SED with least deviation.

It also lists various parameters of stars, including calculated masses and ages, in a separate output file. SED fitting is done after YSOs of various classes are identified (in this case, Classes I and II only). The Python code and other details are given in future sections.

2 My Project

2.1 Objective

To create mosaic images of NGC 7538 in the four IRAC channels (3.6 μm, 4.5 μm, 5.8 μm, 8.0 μm), conduct photometry in each of the bands, identify YSOs using specific techniques and fit their SEDs.

2.2 Procedure (Overview)

The procedure followed in this project is as follows –

i. The data from the SHA is basically a collection of *.fits* image files (in all four channels). They consist of basic calibrated data (**bcd.fits*), corresponding uncertainty files (**bunc.fits*) and image masking files (**bimsk.fits*). These files need to be overlapped and mosaicked using MOPEX (Mosaicker and Point-Source Extractor).

ii. Photometry is carried out using one of IRAF's (Image Reduction and Analysis Facility) packages called *digiphot*. Its subpackage *daophot* has various commands, which make photometry a simple matter of using the right ones.

iii. The output is a list of all stars, along with their various parameters (positions, magnitudes, errors) in all four channels. The next step is to match the stars in all the channels using the *tmatch* command in the *stsdas* package of IRAF. This finally gives us a comprehensive list of stars detected in all four wavelength bands.
iv. The most crucial process is the identification of YSOs from this list. This can be done by filtering the stars using the process described in the *Appendix A* of the paper by Gutermuth et al. 2009.
v. Finally, SED fitting for the filtered Class I and Class II is carried out using the Python SED Fitter package, and the output plots are identified. The process more or less follows what is done in the paper by Sharma et al. 2016.

2.3 IMAGE MOSAICKING USING MOPEX

As mentioned before, data from the SHA is divided into various directories containing **bcd.fits*, **bunc.fits* and **bimsk.fits* image files.

Firstly, appropriate input list files for MOPEX are made. The various steps followed are as follows –

i. A list file containing all of the above mentioned file path names (absolute) is made. The LINUX *find* command is used for this task. Moreover, the even-numbered (short exposure) and the odd-numbered (long exposure) files are separated (more on this later). The *find* command, unfortunately, lists only the relative path names of the *.fits* files. This can be remedied using the LINUX *sed* command, which replaces a certain string with another string.
ii. The above file list is sorted numerically using the LINUX *sort* command. This is necessary because MOPEX reads only sorted data. Now, there are six list files – two (short and long) for each of the **bcd.fits*, **bunc.fits* and **bimsk.fits* image files.

iii. The LINUX *grep* command is used to read each of the six list files, and further separate them based on their wavelength channel. Now, there are 24 list files.
iv. One must make sure that each of the six files (for a particular channel) has the same number of lines. In other words, they must have same number of image files listed. If, by chance, it is not so, then they must be made so. This is very necessary to run MOPEX.

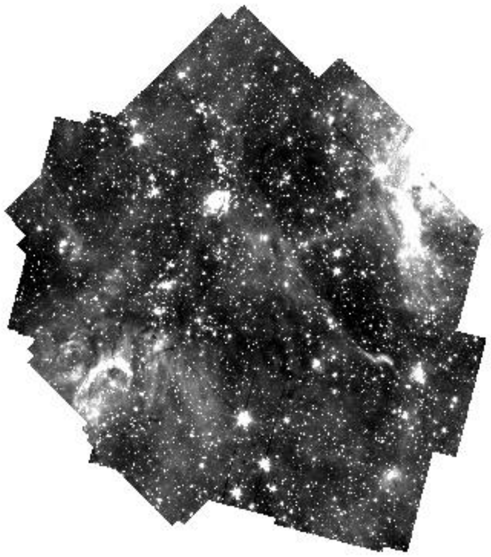
(**Note** – This is not the only method in which the input list files can be made. This is the method I have used.)

The next step is to feed these input files into MOPEX. This input is given through *.nl* name list files. These files are present (by default) in the *cdf* directory of MOPEX. The syntax is ready-made and the only information to fill in are the addresses of the various input list files and output *.fits* mosaic files. Three *.nl* files are used for each channel. They are as follows (to be run in chronological order) –

i. ***overlap*.nl*** **–** The input to this is the list file containing long exposure *.fits* images. The output is a *.fits* image and another list file. The command *overlap.pl –n overlap*.nl* is used to overlap all the long exposure files (of a particular channel) and create an overlapped image.
ii. ***hdr_mask*.nl*** **–** The inputs to this are the list file containing short exposure *.fits* images and the output list file of the previous command. The output is a *.fits* image and another list file. The command *hdr_mask.pl –n hdr__mask*.nl* is used to combine the short exposure and long exposure files (of a particular channel) and create an image which has both. This is necessary because long exposures tend to saturate images, and thus must be dealt with separately.
iii. ***mosaic*.nl*** **–** The input to this is the output list file of the previous command. The output is a *.fits* image. The command *mosaic.pl –n*

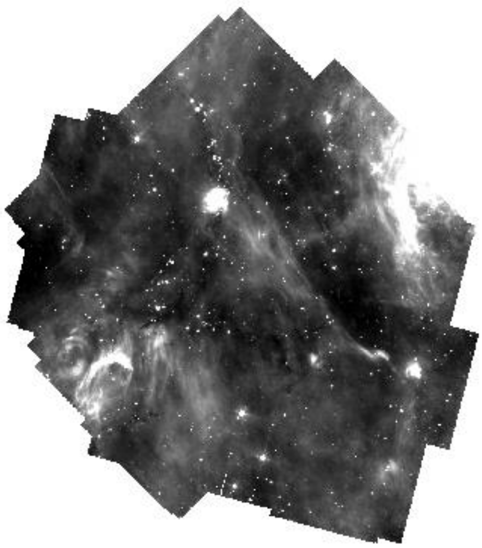
mosiac.nl* is used to create a mosaic image (of a particular channel), which is the final output of MOPEX.

When all three tasks are performed, a *mosaic.fits* image (for each channel) is created. Now, these images are ready for photometry, which is done using IRAF DAOPHOT (see *Fig 2.*).

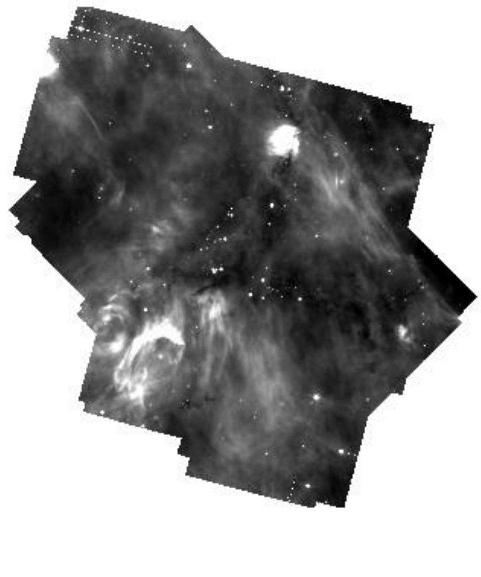


(a)

(b)



(c)



(d)

Fig 2: The mosaic images of NGC 7538 after using MOPEX displayed using SAOImage DS9 (image displayer). (a) ch1 (b) ch2 (c) ch3 (d) ch4

2.4 PHOTOMETRY USING IRAF DAOPHOT

As mentioned before, the main photometry subpackage of IRAF is *daophot*, which can be found in the package *digiphot*. An essential part after photometry is point spread function (PSF) correction, which can also be done using *daophot*. The PSF describes the response of an imaging system to a point source. In other words, point sources are not seen as point sources, but are spread over multiple pixels.

Before carrying out all the *daophot* commands, one must make sure all their parameters are adjusted according to one's needs, which can be edited using the command *epar*. They are –

- ***findpars*** **–** Star detection parameters (detection threshold *threshold*, mark detections *mkdetections*)
- ***datapars*** **–** General star parameters (full-width half-maximum of PSF *fwhmpsf*, standard deviation of sky background *sigma*, minimum and maximum good data values *datamin* and *datamax*).
- ***centerpars*** **–** Centering parameters (centering algorithm calgorithm, center data width *cbox*).
- ***fitskypars*** **–** Sky fitting parameters (sky fitting algorithm salgorithm, sky annulus *annulus* and *dannulus*).
- ***photpars*** **–** Aperture parameters (aperture radius *apertures*, zero magnitude *zmag*).
- ***daopars*** **–** PSF parameters (PSF radius *psfrad*, fitting radius *fitrad*).

For the four IRAC channels, there are a few parameters which need to be edited. First of all, the images in the four channels must be calibrated so that their fluxes normalize. This is done by dividing the respective *mosaic.fits* images by certain pre-determined factors (see *Table 1*.). This can be done using a command *imarith* in the subpackadge *ccdred* of the package *imred* (IRAF > *imred* > *ccdred* >

imarith). The only inputs to this command are the *mosaic.fits* file, the operator (division '/') and the operand.

λ (in μm)	Flux conversion (mJy/sr to DN/sec)
3.6	0.1088
4.5	0.1388
5.8	0.5952
8.0	0.2021

Table 1: Photometric calibration for IRAC channels.

The *fitskypars* parameters *annulus* and *dannulus* must be set to the values 3 and 4 respectively (in pixels) as this is the most suitable sky annulus (for IRAC) to determine the PSF model.

The *photpars* parameters *apertures* and *zmag* must also be changed for each channel (see *Table 2.*). This is because the aperture radius and zero magnitude point for each channel is different.

λ (in μm)	Aperture correction	Zero point
3.6	1.125	19.67
4.5	1.120	18.93
5.8	1.135	16.85
8.0	1.221	17.39

Table 1: Aperture corrections and zero points for IRAC channels.

Now, the commands are ready to be used. They are as follows (to be run in chronological order) –

i. ***daofind –*** It is used to identify stars from the *mosaic.fits* image file using a pre-defined algorithm. It reads the *datapars* and *findpars* parameters. The input to this task is the *mosaic.fits* image. The output is the star list (star ID, coordinates, sharpness, roundness, initial magnitude) *.coo.?* file.

ii. ***phot*** **–** It is used carry out aperture photometry, to calculate magnitudes and respective errors of the star list made using *daofind*. It reads the *datapars*, *centerpars*, *fitskypars* and *photpars* parameters. The inputs to this task are the *mosaic.fits* image and the *.coo.?* file. The output is the photometry (star ID, coordinates, magnitude, magnitude error) *.mag.?* file.

iii. ***pstselect*** **–** It is used to select certain isolated bright stars from the *mosaic.fits* image, called PSF stars. These PSF stars are used for calculating the PSF of the image. If they are not isolated, then their PSFs become distorted. The *pstselect* task can be performed interactively or non-interactively. It reads the *datapars* and *daopars* parameters. The inputs to this task are the *mosaic.fits* image and the *.mag.?* file. The output is the PSF star list (star ID, coordinates, magnitude, sky values) *.pst.?* file.

iv. ***psf*** **–** It is used to calculate the PSFs of the selected PSF stars. The PSFs can be averaged, and this model can be applied to the others. The *psf* task can be performed interactively or non-interactively. It reads the *datapars* parameters. The inputs to this task are the *mosaic.fits* image, the *.mag.?* file and the *.pst.?* file. The outputs the star list (star ID, coordinates, magnitude, sky values) *.pst.?* file, the star group (star ID, group ID, coordinates, magnitude, sky values) *.psg.?* file and the PSF *.fits* image.

v. ***allstar*** **–** It is used to apply the calculated PSF model to all the stars present in the *mosaic.fits* image. It reads the *datapars* and *daopars* parameters. The inputs to this task are the *mosaic.fits* image, the *.mag.?* file, the *.psg.?* file. The outputs are the photometry (star ID, coordinates, magnitude, magnitude errors, chi, sharpness) *.als.?* file, the rejection (star ID, coordinates, magnitude, magnitude errors, chi, sharpness) *.arj.?* file and the subtracted *.fits* image.

The four (for each channel) *.als.?* files are the final products of photometry. The only thing left to do now is to identify the YSOs in the star list.

2.5 FILTERING YSOS

The first thing to be done is to extract the column data from the *.als* file. This is done using the *txdump* command of IRAF (IRAF > *txdump*). The star ID, coordinates, magnitude, magnitude error, chi and sharpness columns are extracted.

cl> *txdump *.als.? ID, XCENTER, YCENTER, MAG, MERR, SHARPNESS, CHI yes > output*

The second step is to convert the coordinates of each star (given in X and Y pixels relative to the *.fits* image frame) to Right Ascension and Declination (in degrees, upto six decimal places). This is done using a command *xy2sky* on the LINUX terminal.

user@comp:~$ *xy2sky -d -n 6 *.fits @xy > radec*

The third step is to match the common stars in the four channels based on their Right Ascension (column 2) and Declination (column 3) values. The limiting threshold used in this case is 3 arc seconds (or 8.3333×10^{-4} degrees), which is of the order of the aperture radius. This is done using the *tmatch* commands of the *stsdas* package of IRAF (IRAF > *stsdas* > *tmatch*). Matching of the four channels is done pairwise.

stdas> *tmatch input1 input2 output 2,3 2,3 8.3333E-4*

Now, the actual filtering of stars can begin. In this project, two phases of filtering are done, which go exactly as that in the *Appendix A* of the paper by Gutermuth et al. 2009. The LINUX command *awk* is invaluable throughout this process, and should be used intelligently.

For the Phase II of the process, one needs to download the 2MASS data for NGC 7538 (available at the Infrared Science Archive IRSA) in the three wavelength bands J (1.235 μm), H (1.662 μm) and K (2.159 μm). Then, the *tmatch* command is used to match stars in J, H and K bands to those in channels 1 and 2 of IRAC.

Phase 1

Phase 1 is only applied to those stars with magnitude errors $\sigma < 0.2$ in all four wavelength bands. Many erroneous sources are eliminated using the equations given below (Gutermuth et al. 2009).

Firstly, active star forming PAH (polycyclic aromatic hydrocarbon) galaxies are eliminated. PAH emission yields very red 5.8 μm and 8.0 μm colours.

Any source which satisfies all of the below conditions is considered to be a PAH galaxy (see *Fig 3.*).

$$[4.5] - [5.8] < (1.05/1.2) \times ([5.8] - [8.0] - 1)$$

$$[4.5] - [5.8] < 1.05$$

$$[5.8] - [8.0] > 1$$

$$[4.5] > 11.5$$

In addition, any source which satisfies all of the below conditions is also considered to be a PAH galaxy (see *Fig 3.*).

$$[3.6] - [5.8] < (1.5/2) \times ([4.5] - [8.0] - 1$$

$$[3.6] - [5.8] < 1.5$$

$$[4.5] - [8.0] > 1$$

$$[4.5] > 11.5$$

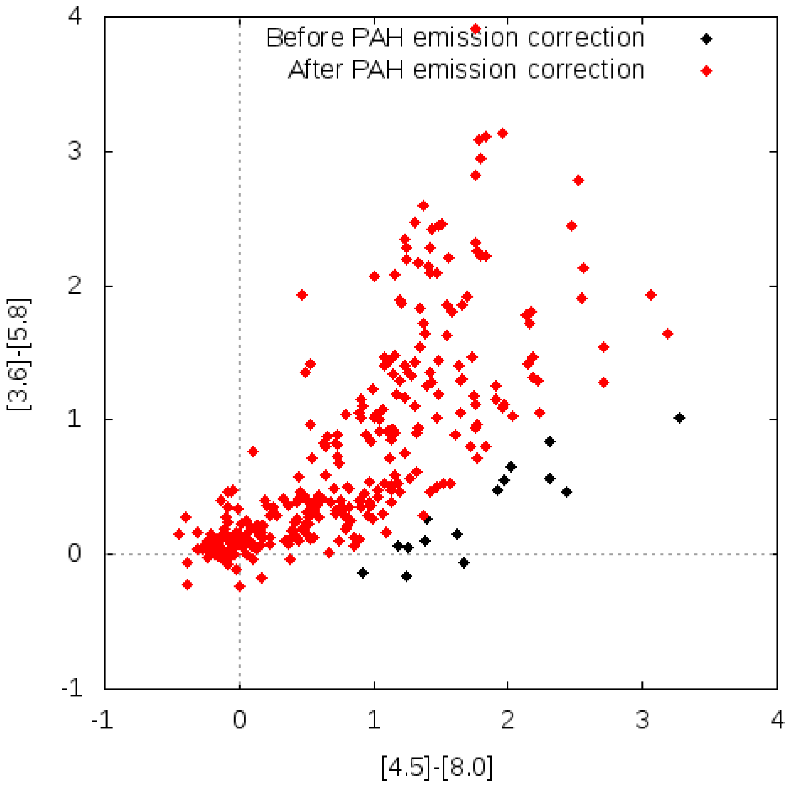


Fig 3: Colour-Colour Diagram for the isolation of PAH galaxies.

Secondly, broad-line AGNs (Active Galactic Nuclei) are eliminated. These AGNs are largely consistent with YSOs.

Any source which satisfies all of the below conditions is considered to be an AGN (see *Fig 4.*).

$$[4.5] - [8.0] > 0.5$$

$$[4.5] > 13.5 + ([4.5] - [8.0] - 2.3)/0.4$$

$$[4.5] > 13.5$$

In addition, any source which satisfies any one of the below conditions is also considered to be an AGN (see *Fig 4.*).

$$[4.5] > 14 + ([4.5] - [8.0] - 0.5)$$

$$[4.5] > 14.5 - ([4.5] - [8.0] - 1.2)/0.3$$

$$[4.5] > 14.5$$

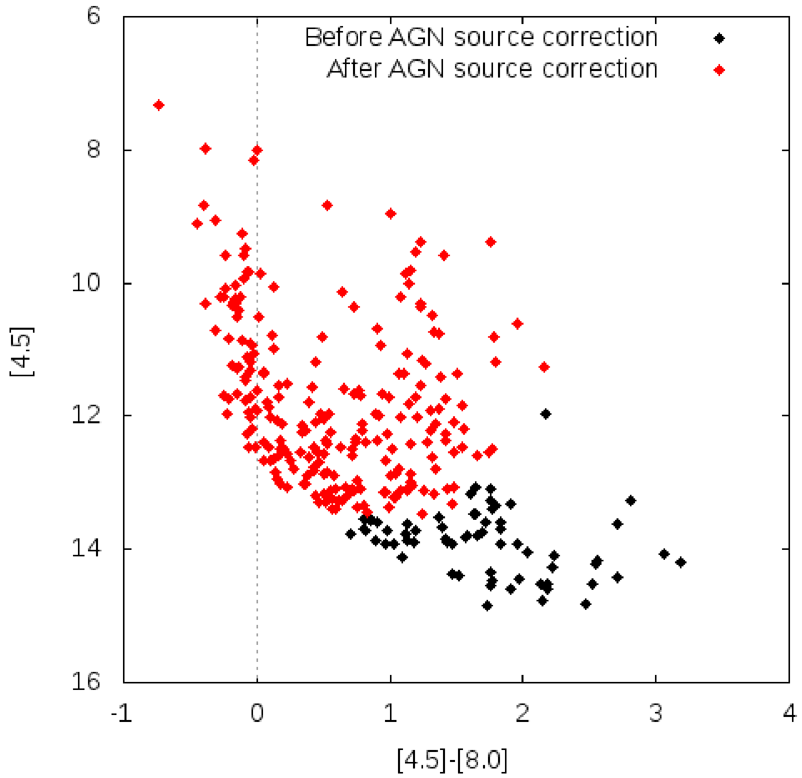


Fig 4: Colour-Magnitude Diagram for the isolation of broad-line AGNs.

Thirdly, shock emission contamination must be eliminated. This is detected in all four wavelength bands of IRAC.

Any source which satisfies all of the below conditions is considered to be dominated by shock emission (see *Fig 5.*).

$$[3.6] - [4.5] > (1.2/0.55) \times (([4.5] - [5.8]) - 0.3) + 0.8$$

$$[4.5] - [5.8] \leq 0.85$$

$$[3.6] - [4.5] > 1.05$$

For other erroneous sources, we use the following sigma values. Each is just the root-mean squared value of the errors in two bands.

$$\sigma_1 = \sigma \{[[4.5] - [5.8]]\}$$

$$\sigma_2 = \sigma \{[[3.6] - [4.5]]\}$$

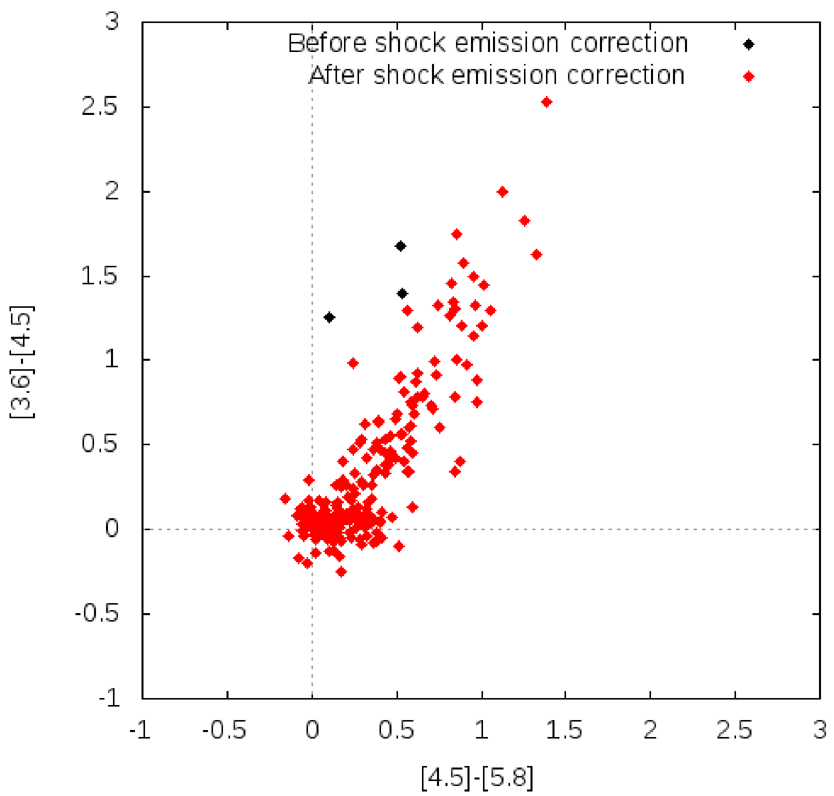


Fig 5: Colour-Colour Diagram for the isolation of sources contaminated by shock emission.

$$\sigma_3 = \sigma \{[[4.5] - [8.0]]\}$$

$$\sigma_4 = \sigma \{[[3.6] - [5.8]]\}$$

Fourthly, sources with PAH emission contaminated apertures must be eliminated. When this happens, there is spurious emission in the 5.8 μm and the 8.0 μm bands.

Any source which satisfies all of the below conditions is considered to be one that has a PAH-contaminated aperture (see *Fig 6.*).

$$[3.6] - [4.5] - \sigma_2 \leq 1.4 \times (([4.5] - [5.8]) + \sigma_1 - 0.7) + 0.15$$

$$[3.6] - [4.5] - \sigma_2 \_ 1.65$$

Now, with most of the spurious data eliminated, one can classify the YSOs into their classes.

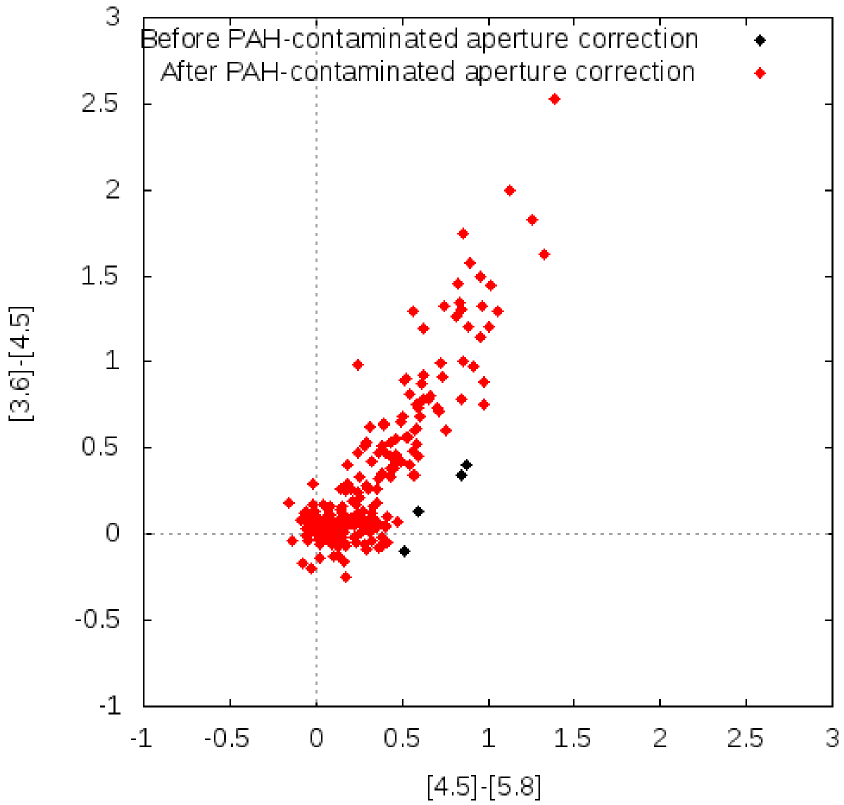


Fig 6: Colour-Colour Diagram for the isolation of sources with PAH-contaminated apertures.

Of the remaining, any source which satisfies all of the below conditions is considered to be a Class I object, due to its particularly red colour (see *Fig 7.*).

$$[4.5] - [5.8] > 0.7$$

$$[3.6] - [4.5] > 0.7$$

Finally, any source which satisfies all of the below conditions is considered to be a Class II object (see *Fig 7.*).

$$[4.5] - [8.0] - \sigma_3 > 0.5$$

$$[3.6] - [5.8] - \sigma_4 > 0.35$$

$$[3.6]-[5.8] + \sigma_4 \leq (0.14/0.04) \times (([4.5]-[8.0]-\sigma_3)-0.5$$

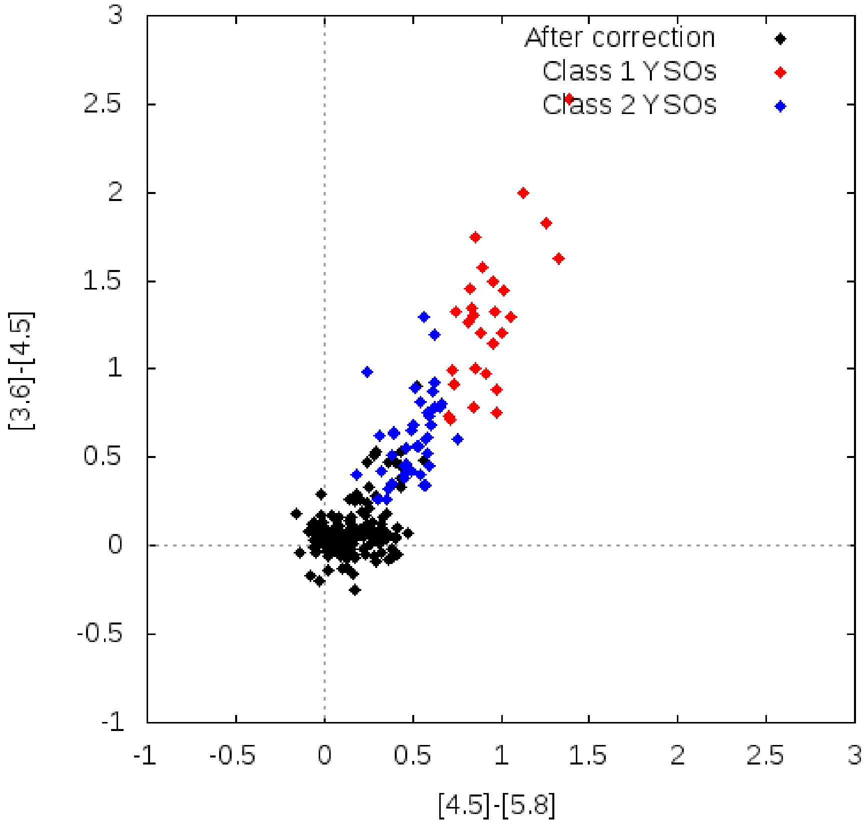


Fig 7: Colour-Colour Diagram showing Class I and Class II YSOs.

Phase 2

As mentioned before, the stars in the J, H and K bands of 2MASS and channels 1 and 2 of IRAC are matched using the *tmatch* command (same threshold of 3 arc seconds or 8.3333×10^{-4} degrees) of package *stsdas* of IRAF. Phase II is applied only to those sources which lack detection in channels 3 and 4, but have readings in the other five wavelength bands. Furthermore, the process is carried out only for those with magnitude errors $\sigma < 0.2$ in all bands (J, H, K, ch1, ch2).

Stars which have no detection (or null magnitude errors) in the J band, but have detection in the K, H, ch1 and ch2 bands are also used in Phase II. Now, these stars are filtered out based on their extinction (colour excess) values. The ones used in this process are given below.

$$(E_{J-H}/E_{H-K}) = 1.73,$$

$$(E_{H-K}/E_{K-[3.6]}) = 1.49$$

$$(E_{H-K}/E_{K-[4.5]}) = 1.17$$

$$C = (E_{[3.6]-[4.5]}/E_{H-K}) = \{(E_{H-K}/E_{K-[3.6]})^{-1} - (E_{H-K}/E_{K-[4.5]})^{-1}\}$$

Firstly, we use these values to find out the intrinsic colour values $[H-K]_0$, $[K-[3.6]]_0$ and $[[3.6]-[4.5]]_0$.

When J band reading is present, the formula given below is used to calculate $[H-K]_0$.

$$[H-K]_0 = \{[J-H]_{meas}-(E_{J-H}/E_{H-K})\times[H-K]_{meas}-0.52\}/\{0.58-(E_{J-H}/E_{H-K})\}$$

When J band reading is absent, the formula given below is used to calculate $[H-K]_0$.

$$[H-K]_0 = \{1.33\times(C[H-K]_{meas}-[[3.6]-[4.5]]_{meas})-0.133\}/\{1.33-1\}$$

Next, the calculated $[H-K]_0$ values are used to evaluate the $[K-[3.6]]_0$ and the $[[3.6]-[4.5]]_0$.

$$[K-[3.6]]_0 = [K-[3.6]]_{meas}-([H-K]_{meas}-[H-K]_0)\times(E_{K-[3.6]}/E_{H-K})$$

$$[[3.6]-[4.5]]_0 = [[3.6]-[4.5]]_{meas}-([H-K]_{meas}-[H-K]_0)\times C$$

For erroneous sources, we use the following sigma values. Each is just the root-mean squared value of the errors in two bands.

$$\sigma_1 = \sigma\,\{[[3.6] - [4.5]]_{meas}\}$$

$$\sigma_2 = \sigma\,\{[[K] - [3.6]]_{meas}\}$$

After this is done, classification begins. Additional YSO are those with dereddened colours. Any source which satisfies all of the below conditions is considered to be a YSO (see *Fig 8.* and *Fig 9.*).

$$[[3.6] - [4.5]]_0 - \sigma_1 > 0.101$$

$$[K - [3.6]]_0 - \sigma_2 > 0$$

$$[K - [3.6]]_0 - \sigma_2 > -2.85714 \times ([[3.6] - [4.5]]_0 - \sigma_1 - 0.101) + 0.5$$

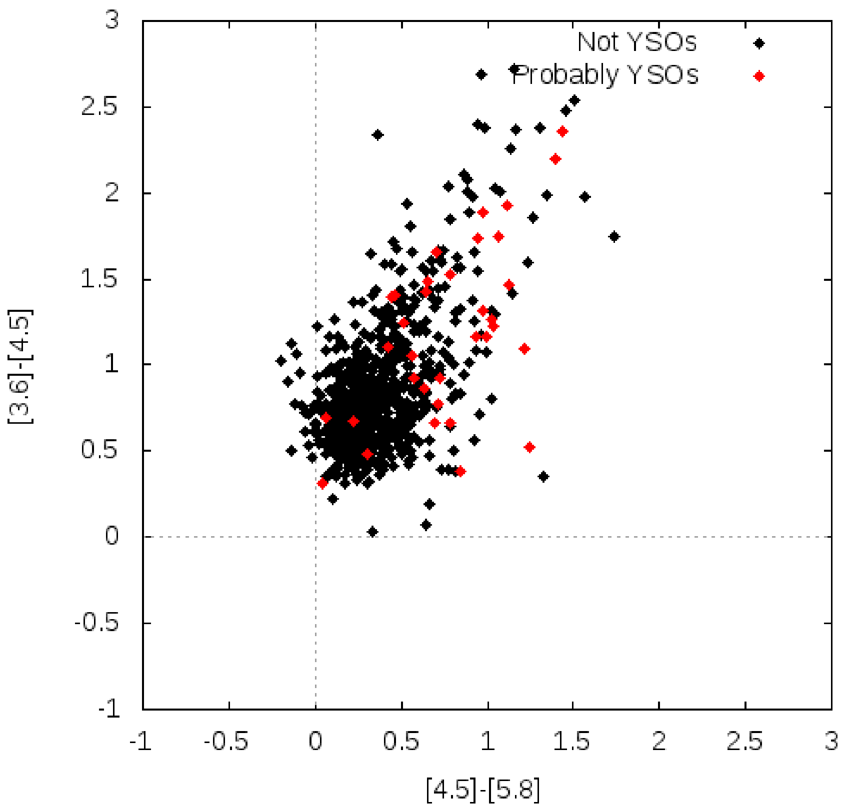


Fig 8: Colour-Colour Diagram identifying YSOs.

Also, any YSO which satisfies all of the below conditions is considered to be a Class I object. The rest are considered Class II objects (see *Fig 10.*).

$$[K - [3.6]]_0 - \sigma_2 > - 2.85714 \times ([[3.6] - [4.5]]0 - \sigma_1 - 0.401) + 1.7$$

All sources classified as Class II objects must have [3.6] < 14.5 and those classified as Class I objects must have [3.6] < 15.

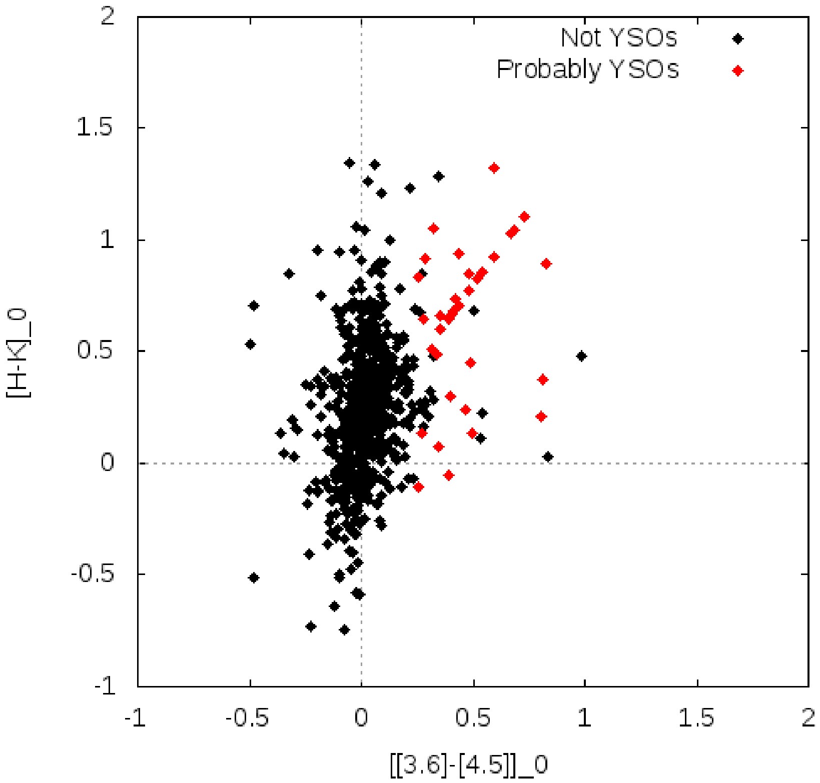


Fig 9: Intrinsic Colour-Colour Diagram identifying YSOs.

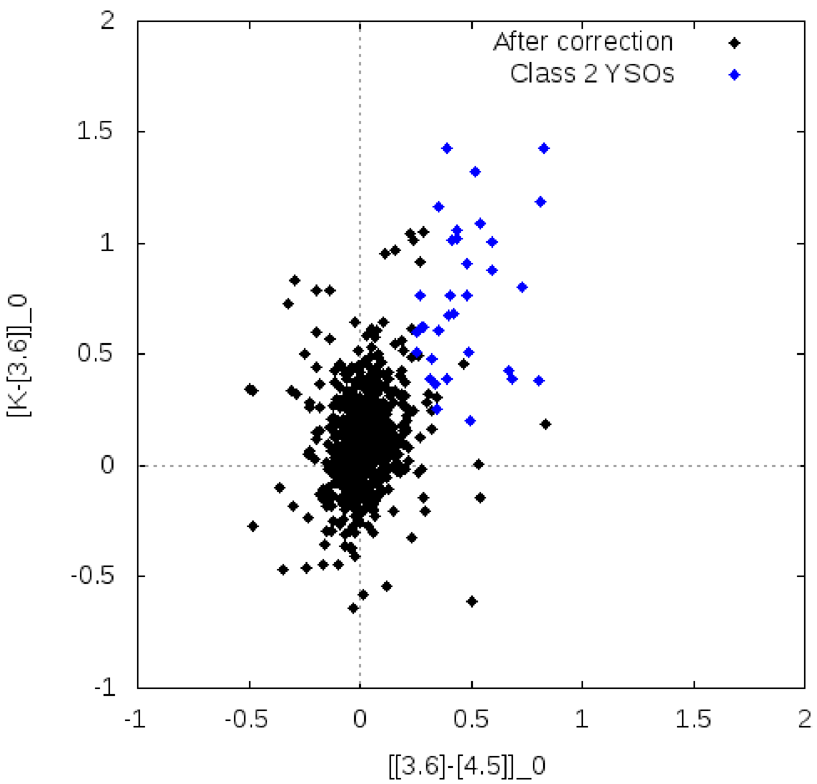


Fig 7: Intrinsic Colour-Colour Diagram showing Class II YSOs (Class I not found).

2.6 SED FITTING

The final part of this project involves fitting SEDs for YSOs and extracting important parameters including ages and masses of individual stars.

Before fitting the SEDs, the magnitudes of the YSOs must be converted first to AB magnitudes, and then to spectral flux densities in mJy (milli-jansky). This is necessary as the Python SED Fitter takes input only in spectral flux densities in mJy.

[1 Jy = 10^{-26} W m^{-2} Hz^{-1}]

AB magnitude is different from the regular magnitude in that it is calibrated in absolute units of spectral flux densities (and not luminous flux densities). Spectral flux density is the radiant flux density (SI unit W m^{-2}) per unit frequency.

The conversion of magnitude to AB magnitude is a simple matter of adding a factor. But this factor differs for each wavelength band (see *Table 3.*).

Channel	J	H	K	[3.6]	[4.5]	[5.8]	[8.0]
Addition factor	0.91	1.39	1.85	2.79	3.26	3.73	4.40

Table 3: Addition factors for converting magnitudes to AB magnitudes

Once this conversion is done, a simple formula is used for conversion of AB magnitudes to spectral flux densities (F_ν) in Jy.

$$m_{AB} = -2.5 \log_{10} (F_\nu) + 8.90$$

$$F_\nu = 10\text{^}(-0.4\ m_{ab} - 8.90)$$

Multiplying the spectral flux density in Jy by a factor of 1000 gives the same in mJy.

Similarly, the magnitude errors (σ_m) must be converted to their respective spectral flux density errors (σ_F).

$$\sigma_F = (F_\nu^2 \times \sigma_m) / 1.09$$

Next, an SED fitting model needs to be downloaded from the SED Fitter website. In this project, the *models_r06* is used as the fitting model. Also, an extinction file *kmh94.par* must also be downloaded.

For a star to be fit using the SED fitter, it must have readings in at least five of the seven wavelength bands (J, H, K, [3.6], [4.5], [5.8], [8.0]). If not, the star is rejected. This new star list must be edited to a particular format which can be inputted to the SED Fitter program. The format of 24 columns is given below.

ID RA Dec P_J P_H P_K P_1 P_2 P_3 P_4 m_J σ_J m_H σ_H m_K σ_K m_1 σ_1 m_2 σ_2 m_3 σ_3 m_4 σ_4

In the above format, the P-columns take the value 0 (if data in that band is absent) or 1 (if data in that band is present), the m-columns are the spectral flux density values in mJy and the σ-columns are the spectral flux density errors in mJy. The subscripts 1, 2, 3 and 4 denote [3.6], [4.5], [5.8] and [8.0] wavelength bands respectively.

Out of all the YSOs isolated from Phase I and Phase II classification, only 23 of them (3 Class I objects and 20 Class II objects) were found to have data in all seven bands (J, H, K, [3.6], [4.5], [5.8], [8.0]), and 21 of them (all Class II objects) were found to have data in five bands (J, H, K, [3.6], [4.5]).

Finally, a Python *fit.py* file is written, with the inputs as described above. The code used is written below.

```
from astropy import units as u

from sedfitter import fit
```

```
from sedfitter.extinction import Extinction

model_dir = '/home/pavan/models_r06'

extinction = Extinction.from_file('kmh94.par', columns=[0, 3],
wav_unit=u.micron, chi_unit=u.cm**2 / u.g)

filters = ['2J', '2H', '2K', 'I1', 'I2', 'I3', 'I4']

apertures = [3., 3., 3., 3., 3., 3., 3.] * u.arcsec

fit('allysodata', filters, apertures, model_dir, 'output.allysodata',
extinction_law=extinction, distance_range=[2.45, 2.85] * u.kpc,
av_range=[2.25, 30.00])

from sedfitter import write_parameters, write_parameter_ranges

write_parameters('output.allysodata', 'parameters.txt',
select_format=('F', 3.))

write_parameter_ranges('output.allysodata',
parameter_ranges.txt', select_format=('F', 3.))

from sedfitter import plot

plot('output.allysodata', 'plots')
```

This is very similar to what is done in the paper by Sharma et al. 2016. The ouputs consist of SED plots of all the selected YSOs and two files. They are *parameters.txt* (containing various parameters for each fitted model) and *parameter_ranges.txt* (containing the ranges of the above parameters).

Two of the parameters, age and mass, are of utmost importance. In the *parameters.txt* file, possible ages and masses (in order of model preference) of each YSO are given. The weighted averages of all the calculated ages and masses of a given YSO are taken to make them closer to the actual values.

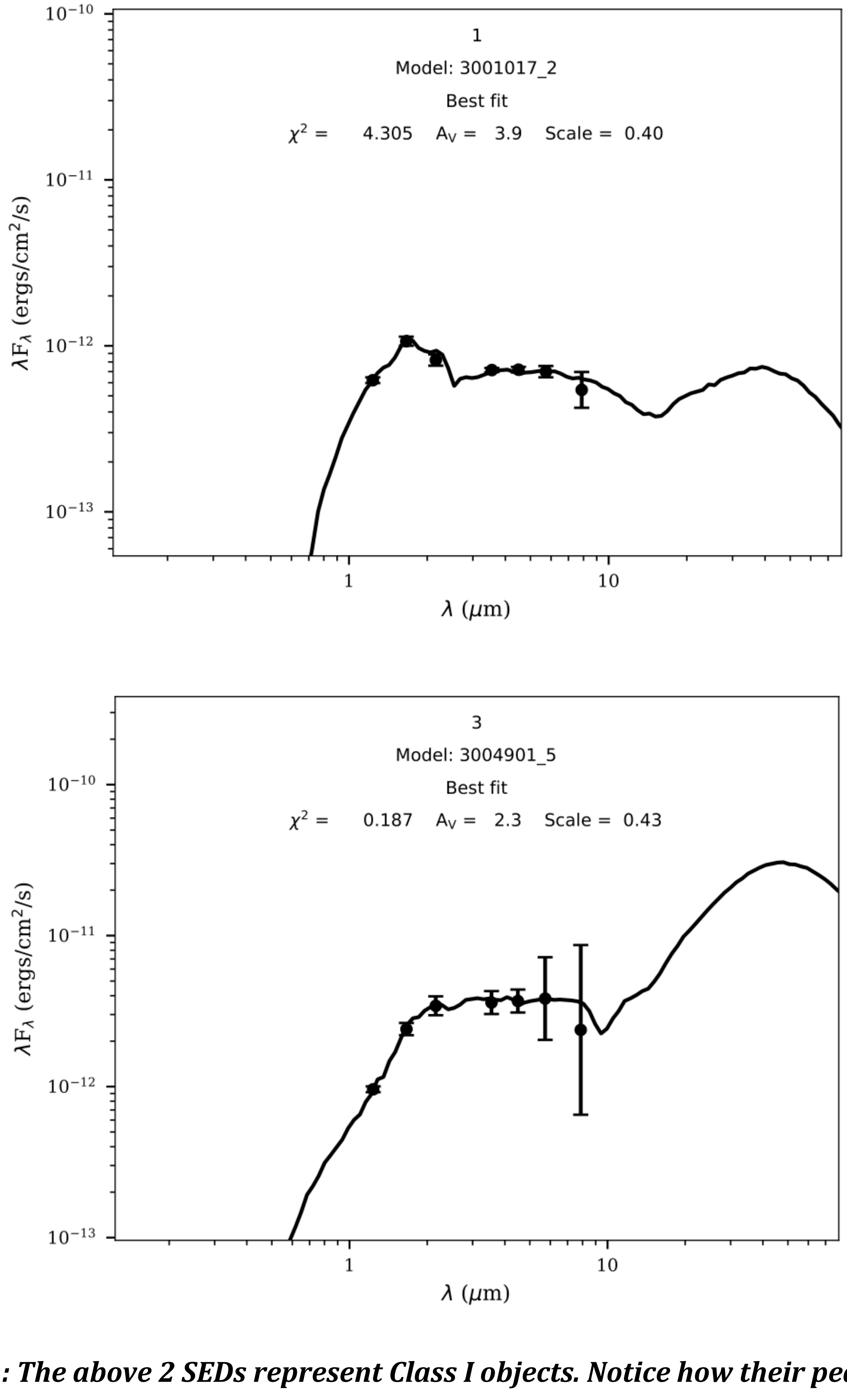
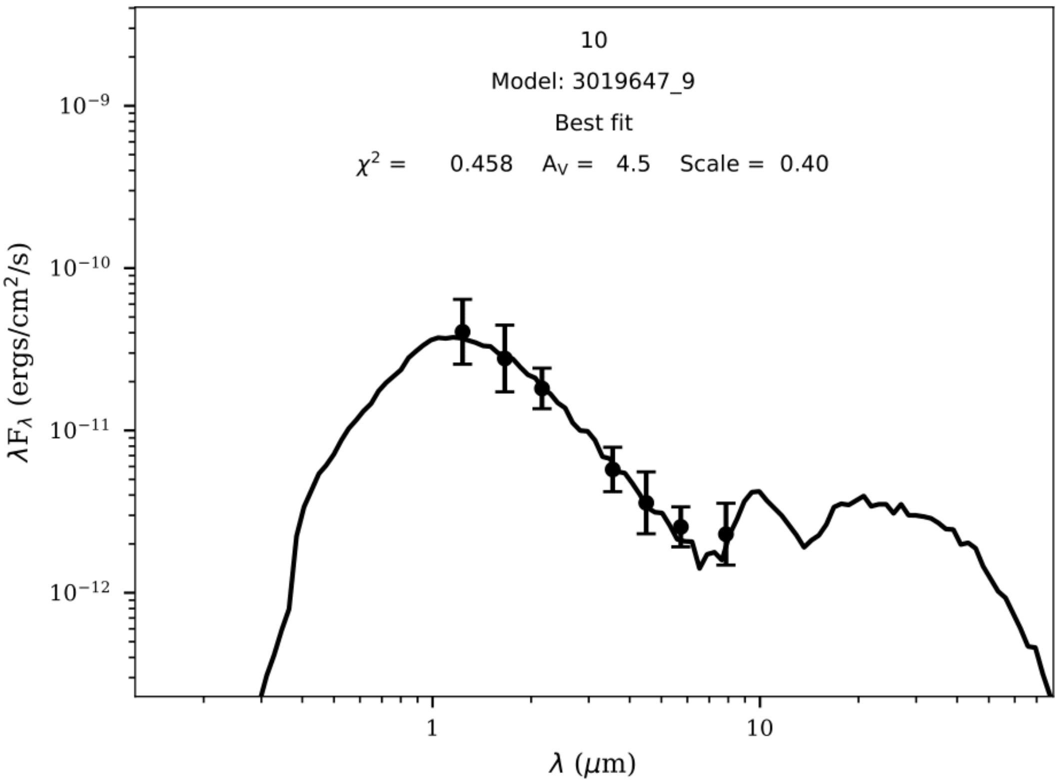


Fig 11: The above 2 SEDs represent Class I objects. Notice how their peaks are not well defined.



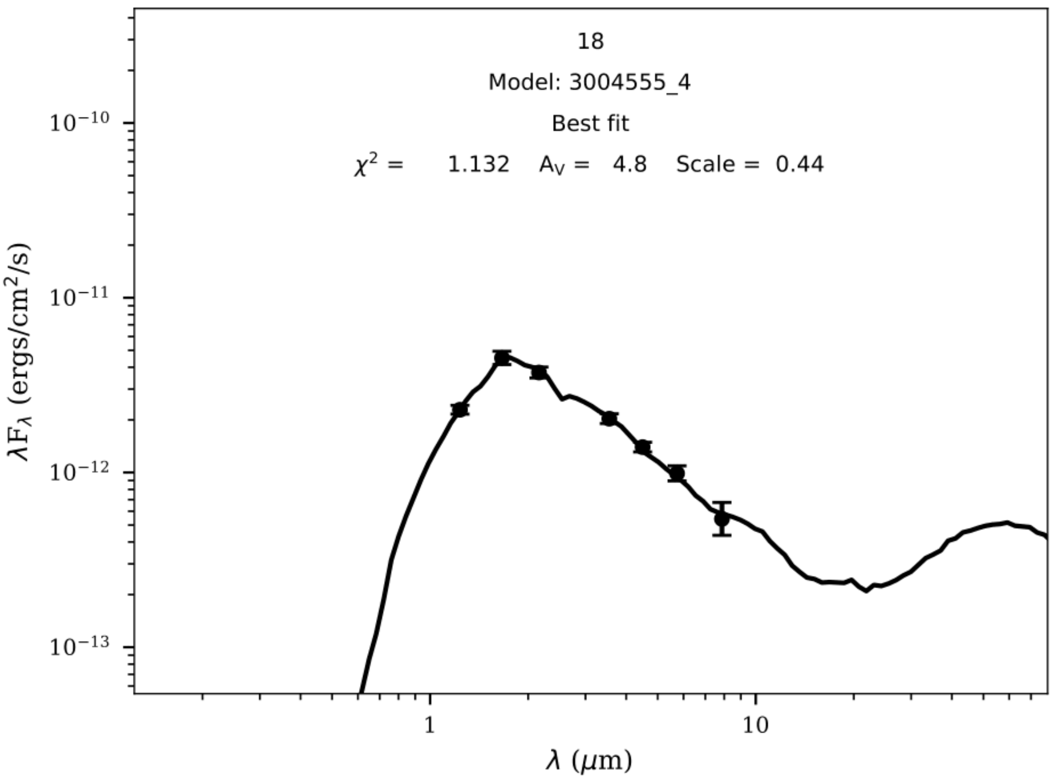
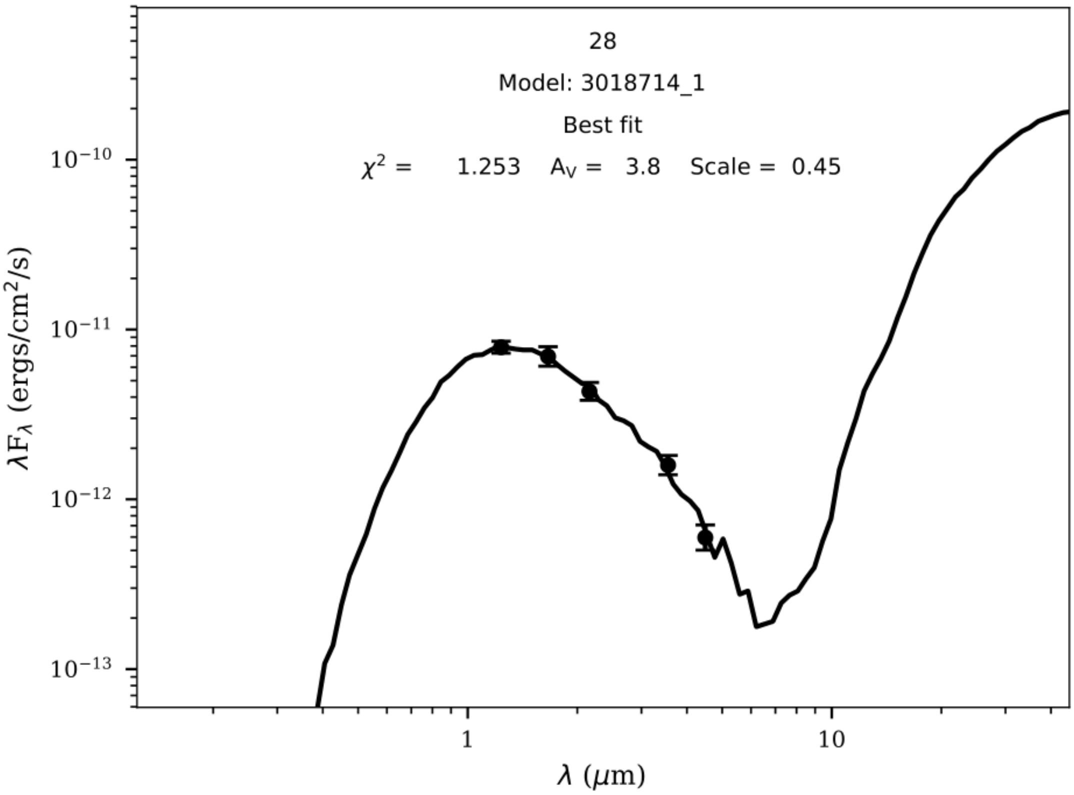


Fig 12: The above 2 SEDs represent Class II objects. Notice how they clearly peak in the ~1 µm wavelengths (far IR fitting may be correct).



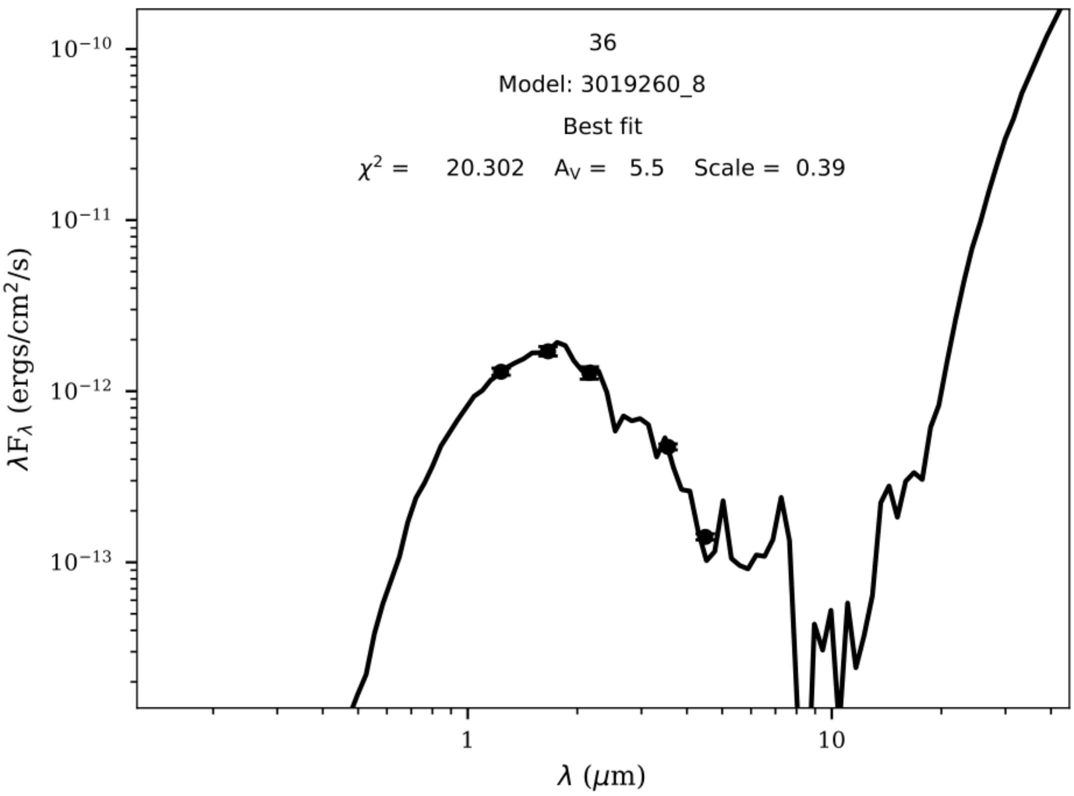


Fig 12: The above 2 SEDs represent Class II objects. Notice how they clearly peak in the ~1 μm wavelengths (far IR fitting may be wrong).

2.7 RESULTS

Spitzer data for NGC 7538 was mosaicked using MOPEX (for all four channels). Photometry was conducted on these mosaic images, and various star parameters were found.

YSOs were isolated I two phases. In phases I and II, 27 and 0 Class I objects, and 42 and 33 Class II objects were identified respectively.

Finally, SEDs for 44 (3 Class I objects and 41 Class II objects) of these YSOs were fitted, confirming that they were indeed Class I and Class II objects, and the masses and ages of individual YSOs were calculated using weighted averages. Fitting would have been more accurate had there been far IR (MIPS) data too.

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