# AN ANALYSIS OF THE PROTO-PLANETARY DISKS SURROUNDING YOUNG STELLAR OBJECTS IN THE SMALL MAGELLANIC CLOUD

by

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A senior thesis submitted to the faculty of
Ithaca College
in partial fulfillment of the requirements for the degree of

Bachelor of Science

Department of Physics
Ithaca College
March 2010

ITHACA COLLEGE

DEPARTMENT APPROVAL

of a senior thesis submitted by

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This thesis has been reviewed by the research advisor, senior thesis instructor, and department chair and has been found to be satisfactory.

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# ABSTRACT

# AN ANALYSIS OF THE PROTO-PLANETARY DISKS SURROUNDING YOUNG STELLAR OBJECTS IN THE SMALL MAGELLANIC CLOUD

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The following takes a sample of 16 young stellar object (YSO) candidates from the Small Magellanic Cloud (SMC). Using optical spectra from the *SSO* in Australia, infrared spectra from *The Spitzer Space Telescope* and photometric data from the *OGLE II* and *2MASS* surveys we have identified 8 of these 16 candidates are indeed young stars (4 spectroscopically resembling T Tauri and 4 Herbig Ae/Be stars from the Milky Way). All 8 of these stars have protoplanetary disks. The SMC's low metallicity is affecting the star/disk formation process. Our T Tauri stars are 10-100 times brighter than their Galactic counter-parts. We discus Polycyclic Aromatic Hydrocarbons (PAHs) and there use as a probe of the environment of the protoplanetary disk. The metallicity is challenging PAH trends found in Galactic Herbig Ae/Be (HAeBe) stars and some of these trends, due to the metal poor environment, may not be applicable to HAeBe stars in our sample.

# ACKNOWLEDGMENTS

I would like to acknowledge all those who have helped me. A special thanks to Vincent Whitney for obtaining spectral types and temperatures for the sample. A thanks goes to Jordan Hyatt for helping me in the lab. Luke Keller, my research advisor, for teaching me astronomy and helping me through this thesis. I would also like to thank Greg C. Sloan (Cornell University) for helping me learn how to reduce *Spitzer* data and use the data reduction pipeline.

# Chapter 1

# Introduction

There are many factors that contribute to the formation of a planet like Earth. For one, you need a star. The material surrounding a star, its compositions and environment, proximity to other bodies, distance from a star all effect the type of planets that may appear in a solar system. With so many opportunities to diverge most worlds evolve to be much different than our own. We know this because, to date, we have not found another planet like ours. A desire to understand how planets like Earth come to being has been the motivation to research how stars and solar systems form. A critical component of solar system (and eventually planet) formation is the circumstellar disk. The disk is comprised of gases, rocks, ices and dust particles all of which are gravitationally bound to and orbit about a star at the center of the disk. A protoplanetary disk is a circumstellar disk which surrounds a newly formed (young) star and may eventually form planets. The protoplanetary disk is the reservoir of matter from which the planets are assembled. We know that during the birth of a star a protoplanetary disk is formed (see section 2.1) and it is the matter in this disk from which the planets are made. We know that planetesimals are formed in the disk, through accretion or perhaps as a result of a cooling process. A planetesimal is a solid object whose mass is just large enough so that gravity holds it together. These planetesimals than begin to “snowball”. They are lumps of matter which gravitationally draw in more and more material or simply collide and become larger. While we are beginning to have a good understanding of how planetesimals become protoplanets [1] the details are still the subject of debate and further study. Collisions between planetesimals and other protoplanets cause the protoplanets to heat up and melt. This allows the formation of dense planetary cores. The large mass ($\sim 10^{-8} M_{\odot}$ or rather $10^{-8}$ times the mass of our sun) bodies begin to attract gases, forming an atmosphere, which further accelerates the accretion process. This is via the force of friction: interactions between the atmosphere and the faster orbiting material in the disk slows the material (“atmospheric drag”) causing it to fall onto the planet. We also understand how important bombardment is: material that hasn’t been blown away by solar winds rain down on the disks and therefore on planets, adding heat and mass. When the bodies are massive enough to formed a spherical shape by gravity and have cleared away all debris from there orbital path they are planets like the ones in our own solar system. We understand most of the process because of evidence seen on Earth, or from examples of other solar systems mid-formation that we can study. We also now have an appreciation for our location in the solar system. The “green”, or “habitable”, zone (HZ) defines where a planet must reside such that stellar conditions can support life (Water exists in liquid form most of the time). Although much has been learned, it is unanswered and new questions regarding the details of the formation process that continue to drive the study of the stages of star and planet formation. We are still unsure of exactly what takes place between the protoplanetary disk stage and the formation of planetesimals. How does the planetesimal formation process begin? What causes the local clumps of matter that initiates the snowball effect? To learn how this process occurs we must know what variables affect it and how to measure them. For example, metallicity is a measure of the abundance of “heavy elements”; where a heavy element is anything larger than Helium. Scientists suggest that high metallicity in the circumstellar disk may catalyze the planet formation process [4]. Metallicity in circumstellar disks must be studied to understand solar system formation. The shape, or geometry of the protoplanetary disk may also be a factor in planetesimal formation. We will use infrared emission from Polycyclic Aromatic Hydrocarbons (PAHs) as a diagnostic tool to probe the geometries of protoplanetary disks (see section 2.4). To understand solar system formation we must better our knowledge of the protoplanetary disk and its evolution, and that begins with an investigation of how stars are born and how their disks form.

# Chapter 2

# Theory

## 2.1 The Star Formation Model

Stars are born from clouds of interstellar medium (ISM). In particular, the clouds that form stars are cold ($10 - 30K$) and dense ($\sim$ 300 molecules per cubic centimeter). This is not very dense when compared to air at standard temperate and pressure for example ($\sim 10^{19}$ molecules per cubic centimeter) but is extremely dense considering its location in the near-vacuum of space. It should also be noted that the density is not constant throughout the cloud. Star forming clouds are "lumpy", with areas that are hundreds of times more dense the the average for the entire cloud. Since the low temperatures allow for the formation of molecules these star forming regions are called *molecular clouds*. Molecular hydrogen, on average, accounts for 70% of the mass found in these clouds. Also present is helium ($\approx$ 28% by mass) and other gases such as: carbon monoxide ($CO$), water ($H_2O$), ammonia ($NH_3$) and hydrocarbons like ethyl alcohol ($C_2H_5OH$). There are also interstellar dust grains. Accounting for 1% of the total mass of the cloud, interstellar dust contains about half of the "heavy" elements found in the ISM [3]. The dust grains (whose size ranges from a few microns up to about a millimeter are mostly silicates and carbonaceous grains with oxygen, magnesium and iron found in some dusts.

The star formation process begins when the gravity between particles is able to over come the thermal pressure which supports high density region in the cloud. Gravity collapses the cloud and as a result it begins to heat up. The increasing density attenuates the radiation of heat at which point temperature and pressure in the central core (now a *protostar*) increase rapidly. Gas infall continues to increase the mass of the protostar. Now consider figure 2.1. In a given cloud there are particles undergoing random motion. If you were to average the directions over all particles you will conclude that there is no net direction of travel and therefore no net angular momentum. If now we look to any local region (such as a high density region about to collapse under the force of gravity) we will find a preferential direction of travel and consequently a non-zero angular velocity in the region. Naturally, if you sum the local velocities over the entire cloud you will retrieve the expected zero net angular rotation but for a given locality: random motion of the gas and dust particles will give the cloud region a rotation, albeit a slow one. When the region is contracted under the force of gravity this angular rotation is increased due to conservation of angular momentum. The higher rate of rotation causes the remaining cloud surrounding the protostar to flatten into a *protostellar disk*. The interaction and collision of particles in the protostellar disk cause material to fall onto, or accrete, onto the protostar. Accretion continues to increase the mass of the protostar. As the mass increases gravitational forces continue contracting and increasing the core temperature of the protostar. Once the center has reached 10 million kelvin, hydrogen fusion begins and the star is born. The surrounding disk of material remains. Matter orbiting in the disk can coalesce into larger mass objects (such as planetesimals and in due course protoplanets) thus slowly clearing away the debris left behind. This is the stage that we are interested in. Investigating young stars with protoplanetary disks is the first step in understanding solar system formation since the planets form in these disks. Properties of these disks such as chemical composition and geometry are important factors which affect the processes that create planets.

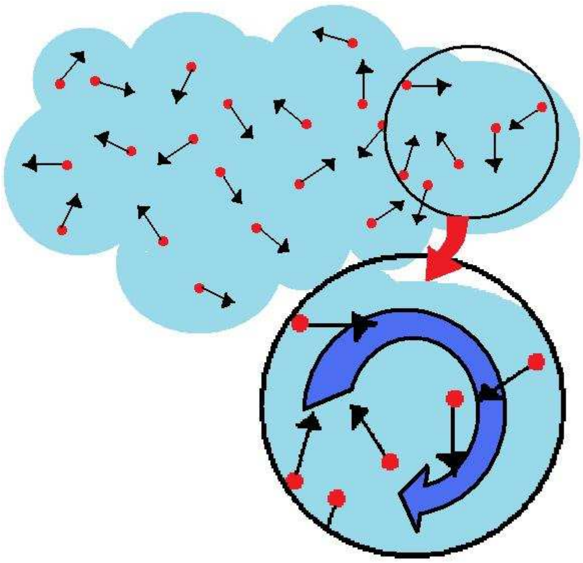

Figure 2.1 (color online) Since the velocity of each particle is in a random direction there is zero net angular momentum when you consider the entire cloud (you are averaging over many particles). If you consider a localized region (enlarged section) one can expect some preferential direction of travel (indicated by the blue arrow) and therefore some non-zero angular momentum which would have, in the case of the entire cloud, canceled out the non-zero angular momenta of other localized regions to achieve the expected zero net angular momentum.

## 2.2 The Sample

The Small Magellanic Cloud (SMC) is a dwarf galaxy approximately $60,000$ parsecs from Earth. It is gravitationally bound to the milky way and shares a gas envelope with the Large Magellanic Cloud (LMC), which is another dwarf galaxy. Both the LMC and SMC are members of our *local group* of galaxies along with our own Milky Way galaxy. Although the SMC is one of the furthest objects visible to the naked eye it can only be seen from the southern hemisphere. What makes the SMC special is its low metallicity relative to the Milky Way. At approximately 20% of solar [5] the SMC is both a very metal poor environment compared to the Milky Way yet close enough to have spatially resolvable star/disk systems. Since metallicity greatly affects the types and abundances of dust [4] an exploration of the disks that form in this environment may shed light on the details of planetesimal formation when compared to analogous processes in the Milky Way. In addition, to study the protoplanetary disks of the target stars we must first identify a sample of stars that *have* disks surrounding them. In our own galaxy we observe T Tauri and Herbig stars: young, low and intermediate massed stars respectively, with circumstellar disks [6]. Optical and infrared images reveal lots of nebulosity. This is typical of active star forming regions. Since the SMC is an active star forming region the theory predicts that we should find young stellar objects (YSOs), like T Tauri and Herbig Ae/Be stars in the Galaxy, and can expect disks to surround them. To find young stars our sample was selected from a YSO candidate catalog (Bolatto et al. 2007) [7]. Candidates are point sources in $H\alpha$ emission images. $H\alpha$ emission is a characteristic of young stars with accreting disks [8]. Our sample also “clumps” with known YSOs on magnitude vs color plots (see figure 2.2). The sample is 16 point source YSO candidates from the SMC (see figure A.1). Before analysis can begin we are tasked with first determining which of the candidates are indeed YSOs and of those that are YSOs, which have circumstellar disks surrounding them.

## 2.3 The Star/Disk System Model

The modeling of stars and their circumstellar disks is important for both analysis and interpretation. Later, inferences drawn from an investigation of Polycyclic Aromatic Hydrocarbons will rely properties of our disk systems. Conclusions will be based on the behavior of material in the disk. It is therefore essential to first ensure the assumptions made are reasonable. Model spectra of stellar photospheres are used to create the Spectral Energy Distributions (SEDs) used later to both identify targets as YSOs by confirming the existence of protoplanetary disks. The photosphere spectra are stellar atmosphere models: referred to hereafter as *Kurucz* models (the name of the atlas we obtained our models from). Inputs to the model are: spectral type, effective temperature, and $\log g$ where $g$ is the acceleration due to gravity of a source [9]. Spectral types and temperatures were calculated by fitting planck functions to the optical spectra and inferring the values (see *Acknowledgments*). The model photospheres allow us to see how the target's spectra compares to that of a bare star with similar properties to the target. when the circumstellar disks of material absorb starlight they become warm and appear as excess emission in the infrared.

## 2.4 Polycyclic Aromatic Hydrocarbons

Polycyclic Aromatic Hydrocarbons (PAHs) are large organic compounds which can often be found in circumstellar disks [10]. They are made up of carbon rings. PAHs are present even here on Earth. PAHs are produced by burning carbon based fuels.

They are also found with deposits of oil and coal. This makes PAHs an extremely valuable diagnostic tool since we can study PAHs in a laboratory and use the results to draw conclusions about the environment in which the circumstellar PAHs are located. One thing PAHs can tell us is how strongly illuminated the circumstellar matter is near the star. PAHs have certain bending modes which change as stellar radiation breaks the C-H bonds of the PAH. Figure 2.3 is an example of what it means for a PAH is "bend". What determines which bending mode occurs depends on the energy the PAH absorbed from the star. As more and more stellar radiation is absorbed by the PAHs the more violently the rings of carbon bend. The amount of energy being absorbed, which is given off by the star, can affect the rate at which the PAHs bend as well as the way in which they bend. The bending frequencies produce electromagnetic waves. In our own Galaxy, PAH emission is common for young stars with protoplanetary disks [11]. PAHs have a very unique emission signature and which is fairly easy to subtract out of a circumstellar disks' spectrum (see section 3.3.1). Different bending modes yield different relative strengths of the features of the PAH spectrum. This will shift the central wavelength ($\lambda_c$) of these features, a measurable quantity. We can determine which bending modes the PAHs are in by noting the wavelengths (and relative strengths) at which the PAHs re-emit the light absorbed from the star. If we know which mode the PAHs are in, we know how illuminated, or processed, the PAHs are. We can then infer conclusions regarding the PAHs location in the disk which can then reveal information regarding the disk's overall geometry. The PAHs re-emit light in several discrete wavelength ranges. The features are at: $6.2\mu m$, $7.7 - 8.2\mu m$ (hereafter $8.0\mu m$), $8.6\mu m$, $11.3\mu m$, $12.0\mu m$ and $12.7\mu m$. The PAH features examined here are all found in the infrared. The *Spitzer IRS* is used to collect the star/disk's infrared spectra, which also contains the PAH emission.

## 2.5 Spectral Properties

The shape of an objects spectrum can provide much information about the object it self. Similar bodies have similar spectra. By looking for the defining characteristics that are in the spectra of different types of common astronomical objects you can accurately identify an unknown source. In order to determine which of our targets are indeed young stars with protoplanetary disks we need to find the defining characteristics of those spectra in our own sample. Stars emit nearly black body radiation therefore their spectra have continuous emission across the optical spectrum with discrete absorption lines. Spectra from S3MC 340160 (figure 2.4) and all YSOs will look like this. This is, for example, in stark contrast to Planetary Nebula (PNe) such as S3MC 220777 (figure 2.4) which is relatively flat through the optical but with several strong forbidden emission lines. A forbidden lines is the result of uncommon electron transitions. In many objects (excluding PNe) the probability of a “forbidden” is incredibility low. In the Milky Way, young stars with protoplanetary disks also have strong $H\alpha$ emission. YSOs should then appear as bright point sources in an $H\alpha$ image (a filter which passes $\approx 6563\mathring{A}$) and have a visible emission line in their spectra.

The last spectral characteristic for a young star with a disk is some evidence for a circumstellar disk. For that we create a spectral energy distribution (SED): tying together the different bands of spectra and separating the disk from the photosphere. Figure 4.2 are the SEDs for the YSOs in our sample. The thick black line is a *Kurucz* model of the photosphere (section 2.3. Overlaid is optical spectra obtained from the *Sidius Springs Observatory* (SSO) in Australia, mid-infrared spectra from the *Spitzer Infrared Spectrograph* (IRS) and photometry data from *OGLE II* and *2MASS* surveys. The YSO in figure 2.5 has infrared excess. The Kurucz models in the SEDs represent a bare star. The additional mid-infrared radiation is coming from a warm protoplanetary disk.

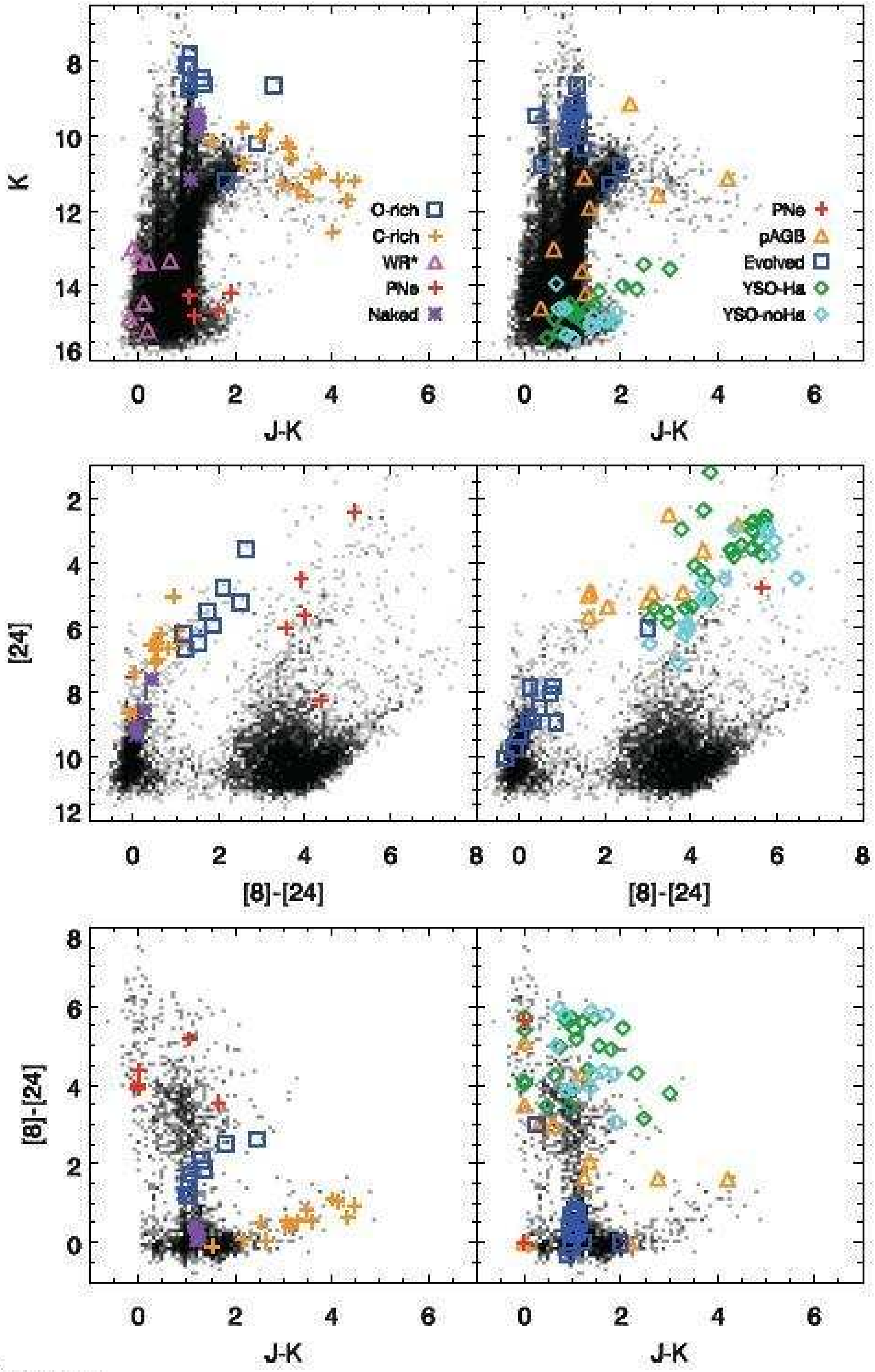

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Figure 2.2 (color online) By plotting the sources of a known type it is seen that sources on these magnitude vs color plots group according to type. Our YSO candidates all clump with known YSOs [12].

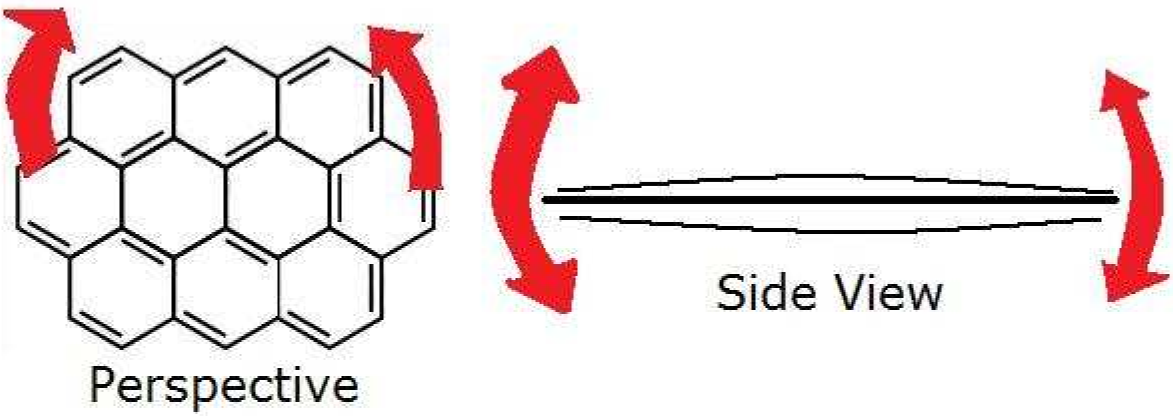
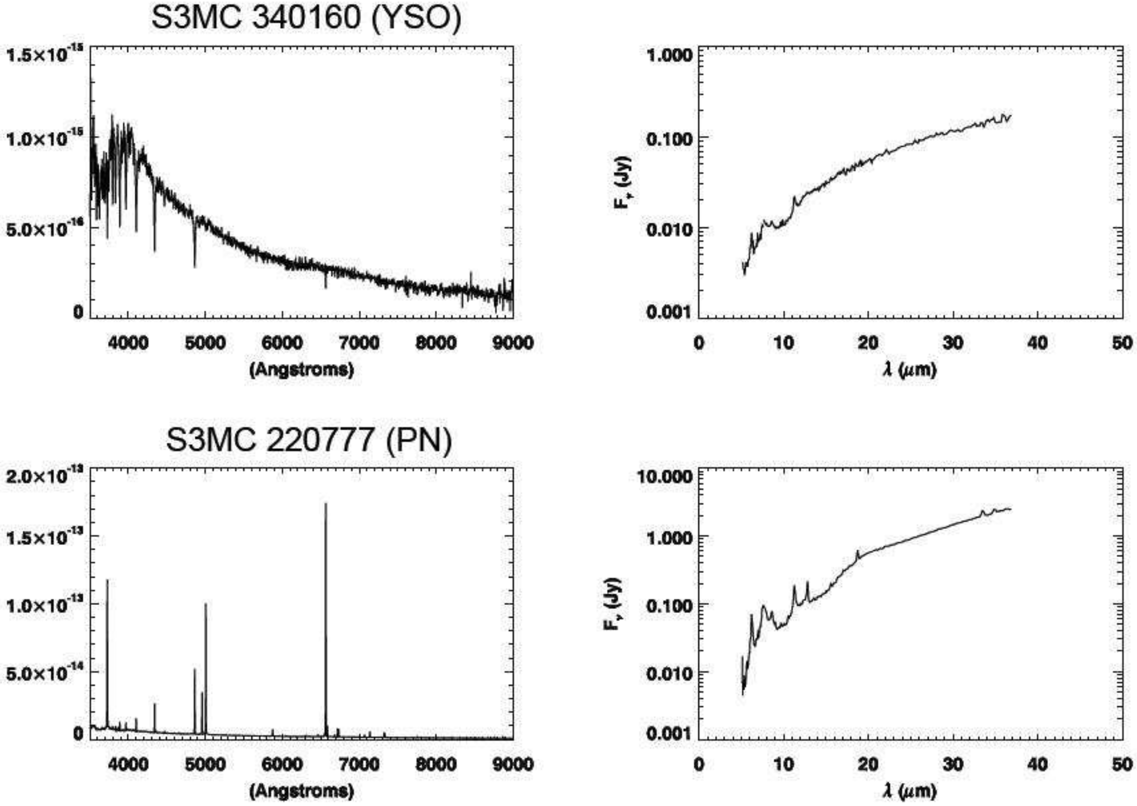


Figure 2.3 (color online) Here is one example of how a polycyclic aromatic hydrocarbon (PAH) may bend. Most PAHs consist of a plane of carbon rings. When excited by stellar radiation the the carbons near the edges of the PAH may begin to oscillate in and out of the plane: the PAH molecule will begin to *bend*. The amount of energy being absorbed can affect the rate at which the PAH bends as well as the ways in which it bends.



S3MC 340160 (YSO)

S3MC 220777 (PN)

Figure 2.4 Optical (left) and infrared (right) spectra of two of our targets. S3MC 340160's (top) optical spectra has a shape characteristic of star spectra. S3MC 220777's (bottom) spectrum on the the other hand looks flat and has forbidden line emission. This is the characteristic shape of a *Planetary Nebula* (PNe).

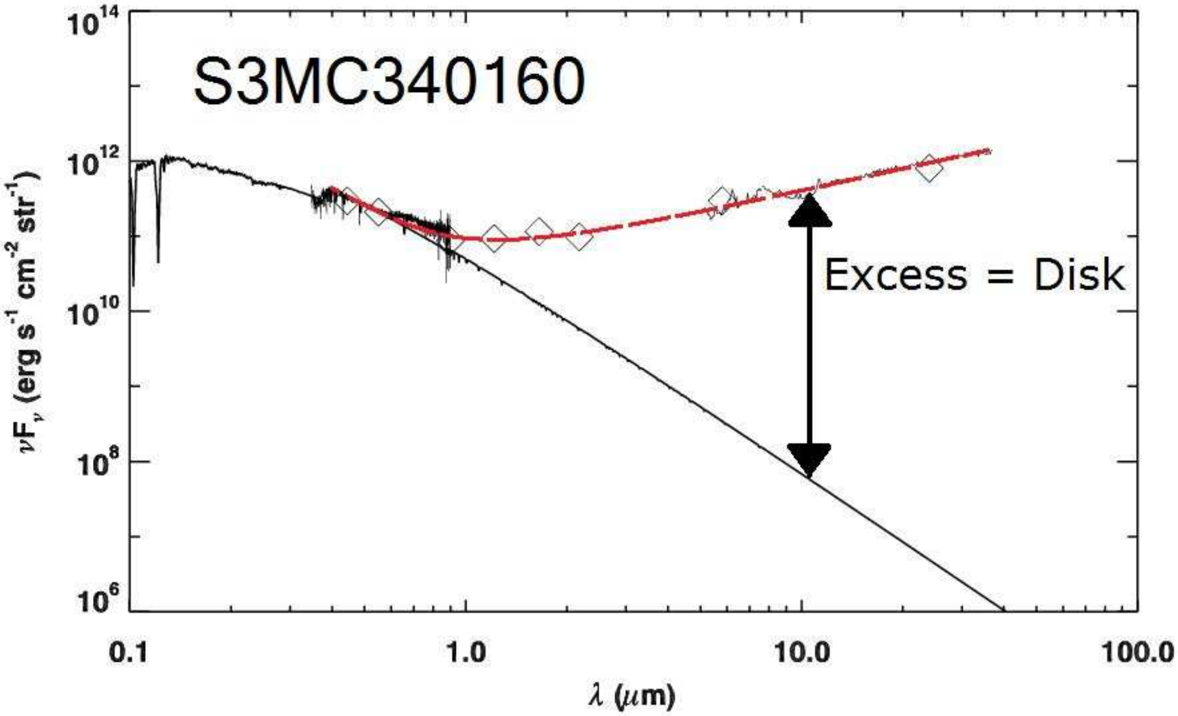


Figure 2.5 (color online) This is a SED of S3MC 340160. In the mid-infrared the actual spectra (lighter lines, diamond points and approximated by the dashed red line) is well above the predicted spectra of just the photosphere (thicker black line). That excess is thermal radiation from a warm circumstellar disk.

# Chapter 3

# Observations and Analysis

## 3.1 Observations

Observations here are in the form of spectra. Mid-infrared spectra were collected with the Infrared Spectrograph on the *Spitzer Space Telescope*. The sample was taken from 16 SMC YSO candidates. Using the Short-Low (SL) and Long-Low (LL) modules of Spitzer's IRS we observed the sample of point-source-like objects. SL module ranges from $5 - 14\mu m$ and LL from $15 - 36\mu m$ with a resolving powers of $R \sim 90$. The observation strategy employed was simple: observing the source in two nod positions so that the back ground noise can be subtracted out. The *SSO* in Australia was used to collect optical spectra ($350 - 900nm$). Photometric data points where obtained by the *2MASS* (J, H and K bands) and the *OGLE II* (B, V and I bands) surveys. A "band" is a bandpass light filter. The name corresponds to the wavelength at the center of the band. J, H, and K are infrared bands centered around $1.26, 1.60$ and $2.22$ microns respectively. B,V and I bands are optical light: standing for blue ($0.44\mu m$), violet ($0.55\mu m$) and indigo ($0.79\mu m$) respectively. The spectra, photometry and data from astronomical databases like Simbad [13] are the observations of the sample.

## 3.2 Spectral Analysis

Our spectral analysis began with temperature estimates, obtained by fitting planck functions to the optical spectra. The optical spectra were also fitted to planck's functions to determine the spectral types. The *Spitzer* data had to be reduced. We used *The Spitzer Science Center's* (SSC) S19 pipeline as well as the calibration method used at Cornell University. The Spitzer IRS Custom Extraction (or SPICE) package's profile, ridge and extract routines were used to extract spectra. After reducing the Spitzer data, calibrating the wavelength scale on the SSO data and using the temperature/spectral type estimates to create Kurucz models (see section 2.3) we constructed the SEDs. The model, optical and infrared spectra and the photometry data are all over laid on one another and normalized to the V band ($\lambda = 550nm$) photometry point. Figure 4.2 are the SEDs for the YSOs in our sample. As you can see, the 8 targets shown all have infrared excess, continuous emission (with discrete absorption) optical spectra. The optical spectra for those same 8 targets is shown in figure 3.1. You can see strong $H\alpha$ emission (see section 4.2 regarding S3MC 340160's $H\alpha$ line). $H\alpha$ emission from a star is a strong indicator that the star is young and interacting with its protoplanetary disk (section 2.2). The infrared excess implies these YSOs are surrounded by warm protoplanetary discs. Two types of stars in our Galaxy are young and are accompanied by protoplanetary discs: T Tauri and the higher-mass Herbig stars. According to our spectral typing: 4 of our YSOs have spectral types like T Tauri and 4 have types suggesting Herbig.

## 3.3 PAH Analysis

As section 2.4 describes, the details of a disk's PAH emission spectra provide information regarding the processing or illumination of the molecules by stellar radiation.

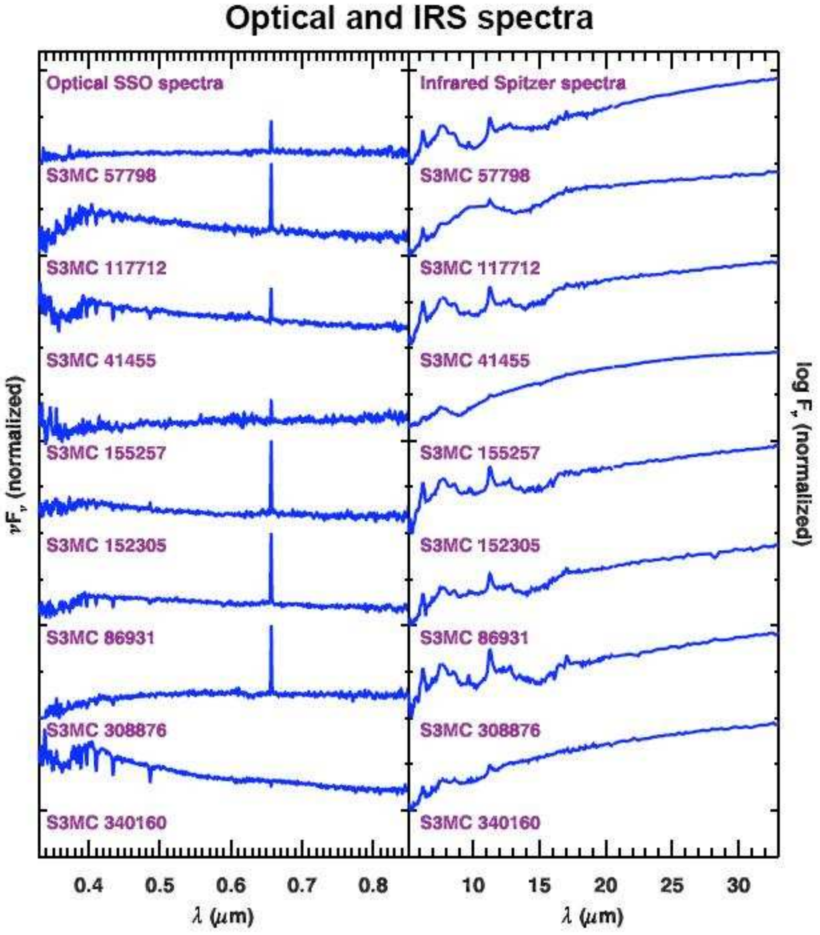


Figure 3.1 (color online) Optical (left) and infrared (right) spectra from *SSO* and *Spitzer IRS* respectively. All 8 of our YSO sources are strong $H\alpha$ emitters. Young stars in our own galaxy have $H\alpha$ emission. Strong $H\alpha$ emission ($\approx 6563\mathring{A}$) from point sources is a good indication that the star is young.

How the material in a circumstellar disk is being illuminated depends on its location in the disk. This makes PAHs a diagnostic tool for investigating disk geometries. To determine where in a disk the PAHs are located we must know how processed they are. Keller et al. 2008 discuses how certain ratios of PAH feature strengths can indicate the level of PAH processing in the Milky Way Galaxy. In addition to calculating the flux ratios of PAH features we must also calculate the flux and central wavelength of all PAH features for each target. This is done using a procedure adapted from the work of G. C. Sloan (Sloan et. al. 2005, 2007).

### 3.3.1 Extracting the PAH Emission

The material in a protoplanetary disk is warm and the entire disk is an emitter of thermal radiation. The infrared excess which indicated the presence of the disk is not only from PAH molecules but dust as well. In order to analyze the PAH features the rest of the continuum must first be removed. This is done by fitting a spline to the spectra. The spline is fit to anchor points (see figure 3.2), which are set at the characteristic wavelengths which mark the continuum at the beginning and end of common PAH emission features. The wavelengths for the anchors are adjusted according to the relative brightness of the features for each individual target, which removes uncertainty caused by molecular emission near/on the feature, asymmetries/peculararties in the PAH feature and any other uncharacteristic shift that the features of a given target may have. After the spline is fit it is subtracted from the spectra. At this point most of the remaining emission is from PAH, with small amounts of residual continuum. Since PAH emission features are generally asymmetric these residuals can impact the calculated central wavelengths ($\lambda_c$). In order to prevent this, a second step is taken which removes the remaining residuals. A line segment is fit to each side of the of the PAH feature. The strength of the feature is the flux ($F_\nu$) found by integrating above this line segment. The central wavelength is found by integrating again, left to right until half the calculated flux is obtained and then again right to left. The two values for $\lambda_c$ are averaged and any discrepancy used to calculate the uncertainty. PAH features shift with the temperature of the illuminating star [14], [15]. PAH features are broad because they are made up of many narrower features [17]. This means that the peak wavelength is less sensitive to shifts caused by temperature changes (the peak wavelength will continue to be the peak of the strongest constituent feature). The central wavelength however, is more sensitive to these shifts and therefore is the more sensitive parameter to probe the PAH environments. The strengths and central wavelengths of each of the target's PAH features can then be used to calculate the flux ratios for the target in question.

### 3.3.2 Flux Ratios, $\lambda_c$ vs Temperature and Spectral Indices

Once the PAH emission is extracted, the fluxes and central wavelengths calculated we can construct a number of analysis tools. The first, flux ratio plots. For intermediate-mass young stars in the Milky Way the ratio of the strengths (fluxes) of certain PAH features correlate to the amount of photo processing of the PAH molecules (Keller et al. 2008). Figure 3.3 is an example of one of the flux ratio plots. Another way in which stellar radiation affects the PAH spectrum is how it shifts the central wavelength of the features. This correlation, which Keller et al. 2008 found in Galactic Herbig Ae/Be stars, supports the notion that star light can change PAH emission. Hotter stars process PAHs more. Since the SMC is so metal poor, there is relatively less dust to absorb stellar radiation.. As seen in figure 3.4 PAHs in these hot star forming region are all very processed and the trend is lost. The third plot, called a Spectral Indices plot, directly infers disk geometry based on PAH emission. A spectral index, or "color" is a difference in flux at two discrete wavelength ranges. The color ($n_{a-b}$) there fore, is calculated as follows [18]:

$$n_{a-b} = \frac{\log\left(\lambda_a F_{\lambda a}/\lambda_b F_{\lambda b}\right)}{\log\left(\lambda_a/\lambda_b\right)}$$

Following Keller et al. 2008 and Furlan et al. 2006: figure 3.5 plots $n_{6-13}$ over $n_{13-30}$. These colors are picked because the wavelengths do not correspond to solid state or emission features. In addition, flux at those wavelengths represent two very

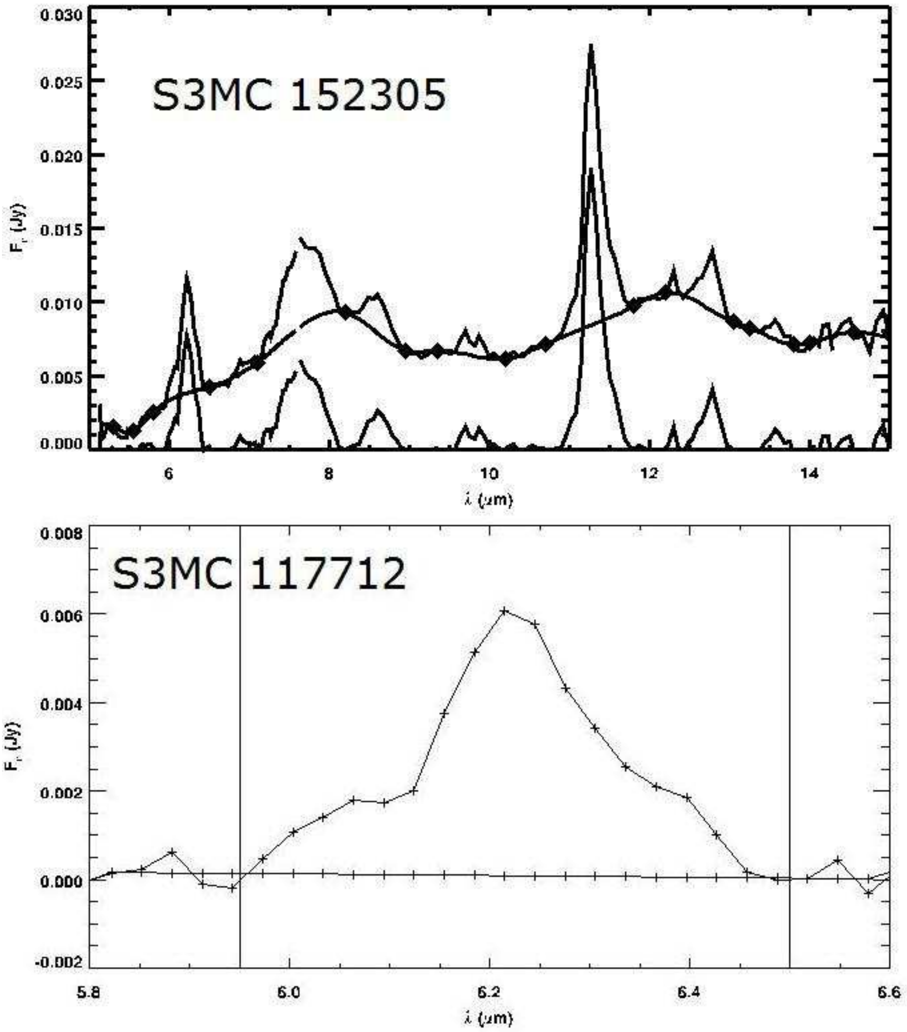


Figure 3.2 *Top:* A spline is fitted to anchors (diamonds). The anchors are at the wavelengths which delimit the PAH features. The spline is then subtracted from the spectrum, leaving the PAH emission and a small amount of residual continuum. *Bottom:* To remove residual continuum from our flux calculations a line segment is fit to either side of a PAH feature (the $6.2 \mu m$ feature in this case). Flux ($F_\nu$) is calculated by integrating between the spectrum and this line segment. Half of the feature's flux is emitted at wavelengths longer than the central wavelength ($\lambda_c$) and the other half at wavelengths shorter than $\lambda_c$.

different parts of the disk, one from hot inner material and the other from cooler material further from the star. This may provide information regarding thermal properties of the disk. Plotting these two colors against each other can reveal the overall shape of the disc. Objects located above the dashed line in figure 3.5 have discs that are radially flared while objects below the line have flattened discs [14].

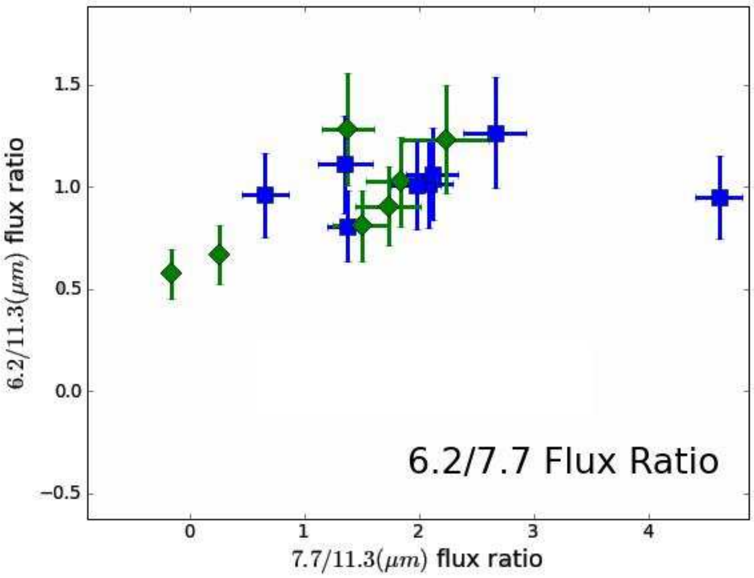


Figure 3.3 (color online) Certain flux ratios correlate to PAH processing. The squares (blue online) are our YSOs. The diamonds (green) are PNe. PAH illumination increases with both the 6.2/11.3$\mu m$ and 7.7/11.3$\mu m$ ratios placing the targets with the most processed PAHs at the top right of the plot. The least processed PAHs are at the bottom left.

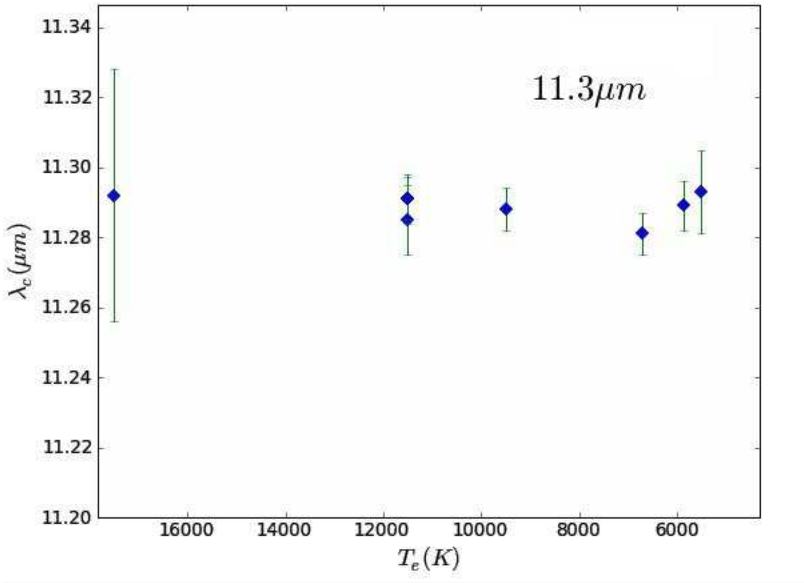


Figure 3.4 (color online) The central wavelength of the 11.3$\mu m$ feature is plotted versus the temperature of the star. Since the SMC is very metal poor the trend found in Galactic Herbig Ae/Be stars is lost.

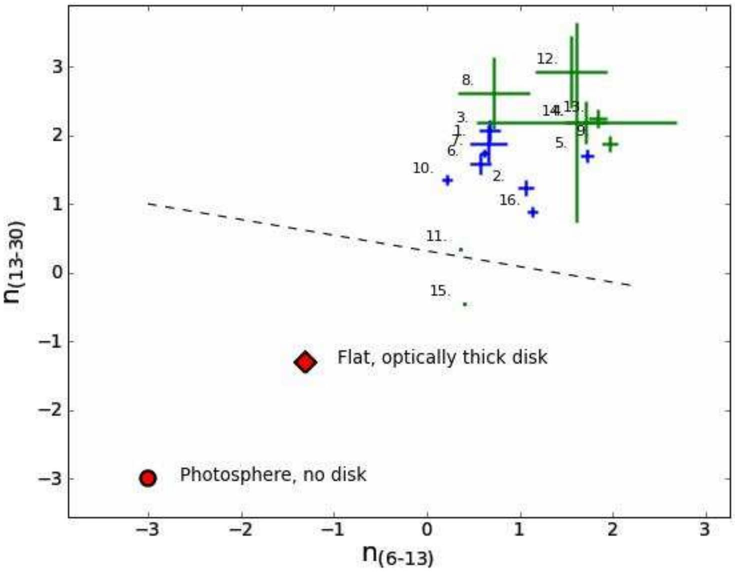


Figure 3.5 (color online) YSOs (blue online) and PNe (green) are plotted based on there spectral colors. The dashed line separates flat, thin disks (below the line) from radially flared disks (above). Each cross represents one targets. The size of the cross correlates to the total flux due to PAH.

# Chapter 4

# Discussion

## 4.1 The Small Magellanic Cloud

The SMC was selected for study for many reasons. First of all, there is simply a shortage of data from this galaxy. In the proposal for the Spitzer IRS data [19], Greg C. Sloan (PI) states "A comprehensive spectroscopic survey of the SMC would revolutionize our understanding of dust in the early Universe. Compared to the nearby LMC [Large Magellanic Cloud], the SMC is in danger of being neglected spectroscopically by the *Spitzer* mission." Particularly, YSO spectra from the SMC, Sloan continues: "YSOs are the most under observed population in the SMC." The reason for observing the SMC also has to do with its metallicity. Identifying YSOs and comparing them to their Galactic counter parts will help examine the role of metallicity in star and protoplanetary disk formation. Four of our 8 YSOs have spectral types which suggest they are T Tauri stars ($G$ and $F$). However, our T Tauri sources are 10-100 times more luminous than T Tauri sources in the Milky Way. Metallicity in the SMC is one fifth of solar [5]. Without dust acting as cooling agent these young stars are relatively hot and could perhaps explain the greater luminosity.

## 4.2 Outliers

One component of the SEDs (section 3.2) was the optical spectra. We were unable to obtain optical spectra for S3MC 11878 and S3MC 155323. We could not, therefore, create SEDs for those targets and they were not included in analysis. Although all 8 of our identified YSOs have $H\alpha$ emission in there optical spectra but S3MC 340160's emission line is veiled (figure 3.1). This is due to an absorption line in the stellar atmosphere. Another target with weak $H\alpha$ emission is S3MC 155257 (figure 4.1). It also has weak $15\mu m$ absorption. We expect these features to be strong in stars like these. A possible explanation is that we are seeing this star's disk edge on. Another explanation could be large amounts of $CO_2$ ice.

## 4.3 Correlations

Figure 4.2 are the SEDs for our 8 YSOs. There spectra are comparable to Galactic Herbig Ae/Be and T Tauri type stars and not PNe (see section 3.2. PNe are commonly mistaken for YSO candidacy because their magnitude over colors are much like YSOs (figure 2.2). The stars in our sample that are identified as T Tauri analogs are 10-100 times brighter than T Tauri stars in our own Galaxy. The use of the $6.2/7.7\mu m$ flux ratio (figure 3.3) are a measurement of PAH processing seems to hold. However, a lack of dust in this low metallicity environment leaves all of the PAHs highly illuminated and the central wavelengths over temperature trend is lost (figure 3.4).

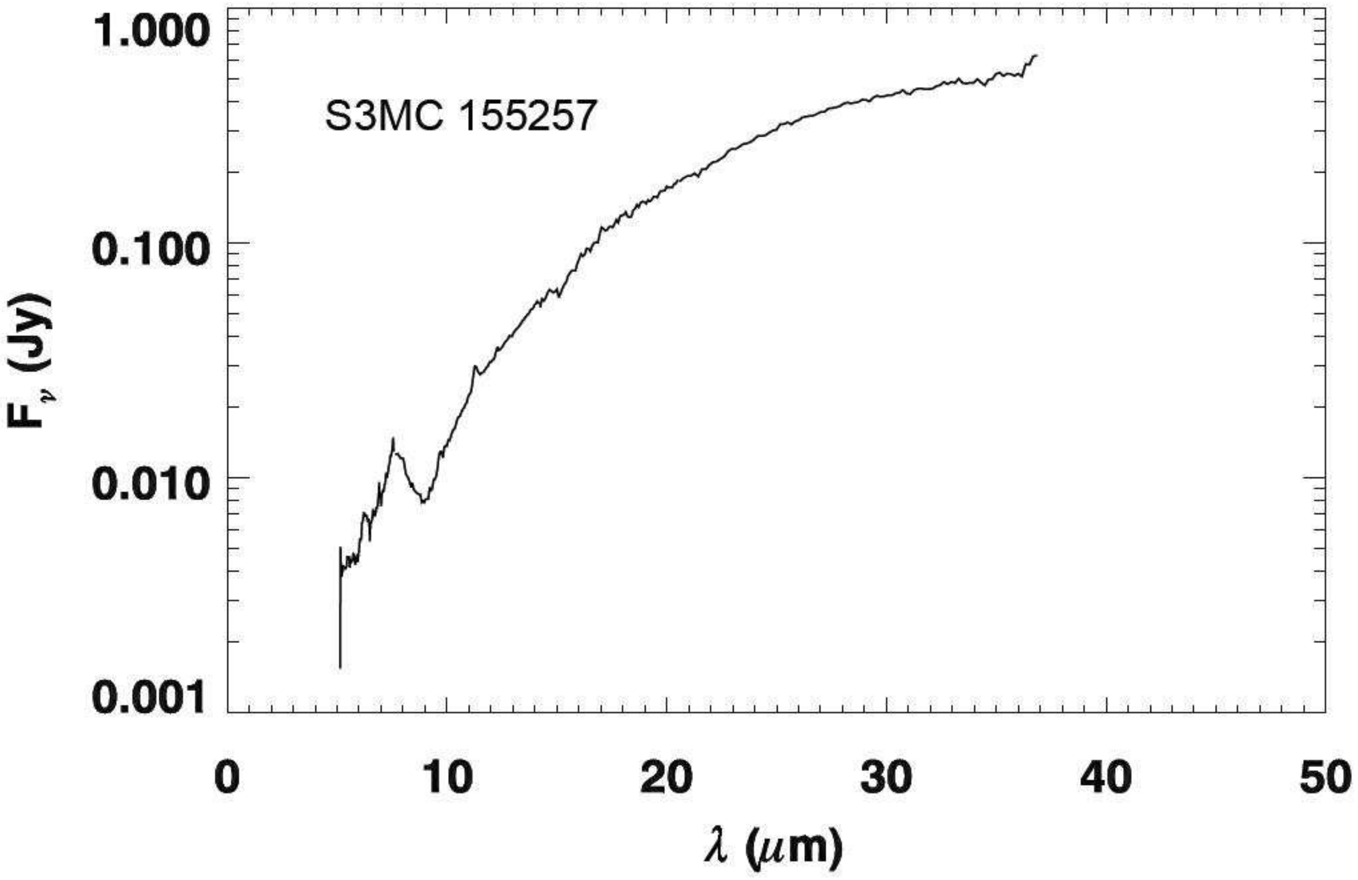


Figure 4.1 Here is the *Spitzer* data for S3MC 155257. The weak $H\alpha$ emission and $15\mu m$ absorption may be caused by large amounts of $CO_2$ ice or we may possibly be seeing the protoplanetary disk edge on.

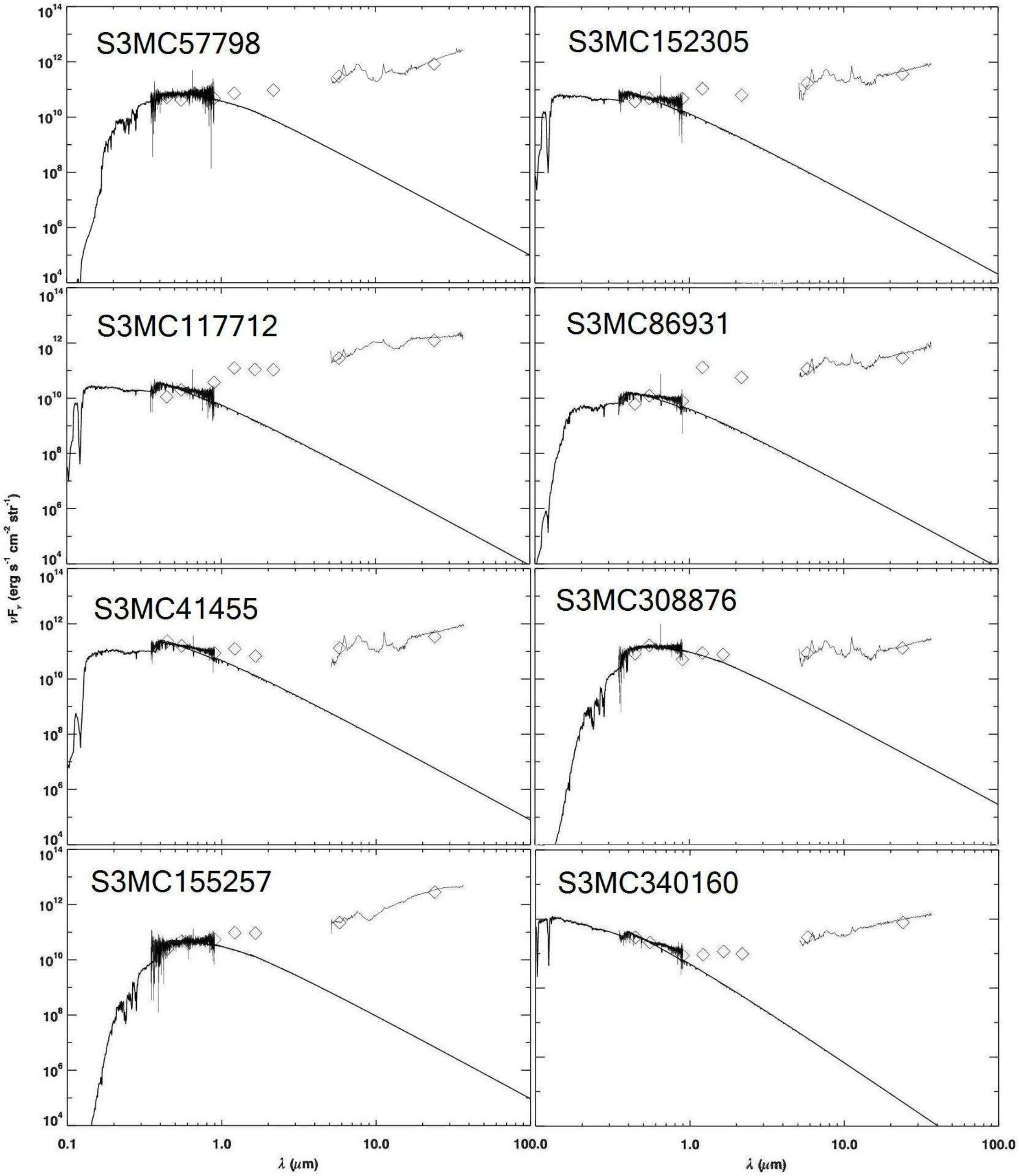


Figure 4.2 Spectral Energy Distributions (SEDs) of our 8 young stars. Thick solid line is a Kurucz model of the spectra for a photosphere with the targets temperature. Overlaid is optical spectra, mid-infrared spectra from the *Spitzer IRS* $(5 - 36\mu m)$, and photometric data points (diamonds) from *OGLE II* and *2MASS* images. The infrared excess seen here is an indicator that a warm circumstellar disk is present.

# Chapter 5

# Summary and Conclusions

In order to gain insight on solar system formation it is imperative to study the protoplanetary disk. Since protoplanetary disks are common around young stars 16 YSO candidates where selected from star forming regions in the SMC. Analysis of their spectra revealed that 8 of the 16 where indeed YSOs with circumstellar disks (4 Herbig and 4 T Tauri). Analysis of the PAH emission coming from these disks will be compared to analogous sources from the Milky Way in an effort to learn the details of disk formation and the role of Metallicity in these processes. The low metallicity has resulted in relatively hot star forming regions. The lack of dust which would of absorbed stellar radiation leaves all the PAHs very processed. This destroys the directly proportional relation ship between the stars temperature and the level of processing of PAHs in the protoplanetary disk. The metal poor environment may also be the cause of greater luminosity. The T Tauri analogs identified in our sample are 10-100 times brighter than there counter parts in the Milky Way. Work must be done to expand the sample as well as fill in the gaps for current sources. Luke Keller will be adding near infrared spectra obtained from the *ESO* in Chile. We must also add ultraviolet and improve our optical spectra. We must also see if these are x-ray sources like T Tauri in the Milky Way.

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# Appendix A

# Appendix Title

Table 1. The targets

| S3MC number | Source type | Temperature (K) | Spectral type | Characteristics of |
|---|---|---|---|---|
| S3MC 57798 | YSO | 6700 K | F4V | T Tau |
| S3MC 117712 | YSO | 11500 K | A2 | Herbig |
| S3MC 41455 | YSO | 11500 K | A2 | Herbig |
| S3MC 129029 | PNe | n/a | n/a | |
| S3MC 155257 | YSO | 11500 K | G8V | T Tau |
| S3MC 152305 | YSO | 9500 K | A2 | Herbig |
| S3MC 86931 | YSO | 13000 K | F0V | T Tau |
| S3MC 38732 | PNe | n/a | n/a | |
| S3MC 308876 | YSO | 16500 K | G2V | T Tau |
| S3MC 18912 | PNe | n/a | B7V | |
| S3MC 100259 | PNe | n/a | n/a | |
| S3MC 220777 | PNe | n/a | O5e | |
| S3MC 329440 | PNe | 6200 K | F4V | |
| S3MC 340160 | YSO | 17500 K | B7V | Herbig |

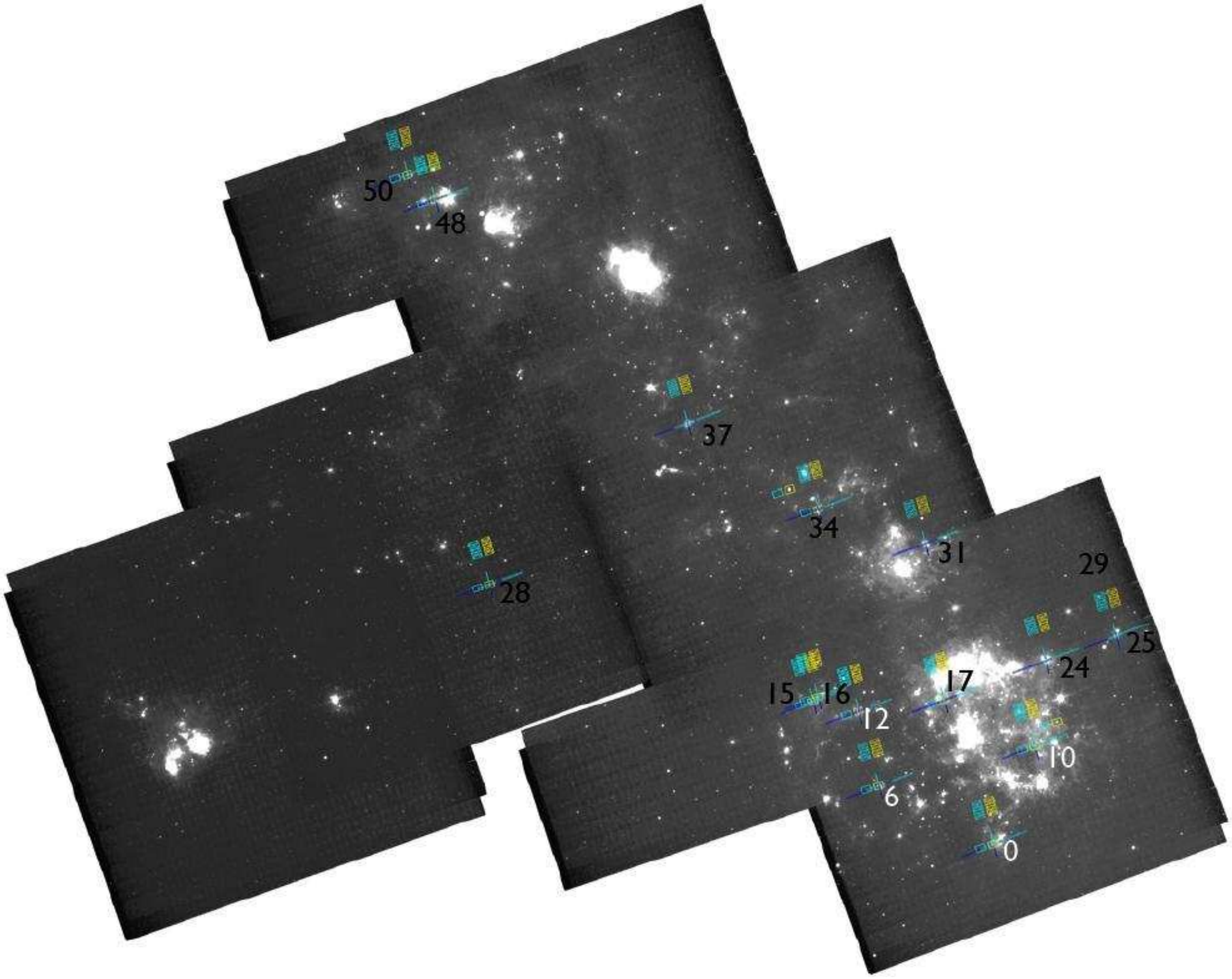

Figure A.1 (color online) Here is a MIPS 24 micron mosaic of the SMC. Overlaid are the AORs used to obtain the *Spitzer IRS* data. The colors have been inverted.