Star Formation in the Serpens Molecular Cloud

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Abstract
The goal of this study is to gain a better understanding of star formation, particularly star formation occurring in the Serpens molecular cloud. In order to accomplish this, we find ages and masses of the stars in the star forming region. Spectra were taken from the Bok 2.3 meter telescope at Kitt Peak, AZ., the WIYN 3.5 meter telescope at Kitt Peak AZ., and the MMT 6 meter telescope at Mount Hopkins AZ. Spectral types and temperatures were determined for each source and the luminosity calculated in order to make Hertzsprung-Russell (H-R) diagrams. The sources were determined to be either association members of Serpens, extinction members, or “other”. H-R diagrams were made for each of the groups to determine ages and masses. According to the H-R diagram, the sources that are likely to be YSOs in Serpens range in mass from 0.12 solar masses to about 3 solar masses and have a median age of 3 million years.

Introduction
The Serpens molecular cloud is located in the constellation of Serpens. It is also in the Gould Belt, which appears as a ring of young stars surrounding our solar system. Serpens is part of a large dark cloud complex called the Aquila Rift. The Serpens molecular cloud is well known for its active star formation. The dense core of the cloud contains a large amount of very young, low mass stars, in various stages of evolution. The core has been shown to consist of two main clumps of gas and dust. One is in the northwest region and the other is in the southeast region. The distance to Serpens has been controversial for many years. Many studies have placed the cloud around 230 pc. However, a recent and more reliable study by Dzib et al places the cloud at about 415 +/- 5 pc. In this study, we use 415 pc for the distance to the Serpens cloud.

Molecular clouds are known to be the birthplaces of stars and clusters of stars. Protostars are formed when dust and gas experiences gravitational infall and begin to heat up. At first, these protostars are obscured by dust and can only be seen at the far-infrared wavelengths. These young objects are known as class 0 protostars. They are the most difficult to detect. As time goes on, the protostar gradually dissipates the infalling envelope and circumstellar disk surrounding it, leading to class I, class II, and class III young stellar objects (YSOs). The latter two classes can be seen in the optical wavelength range as more of the obscuring material is accreted or dissipated. However, there are class 0 and class I stars in the Serpens core as well, corresponding to younger star formation regions than those we have observed. From the disk, protoplanets may form, which also removes disk material. The process of accretion in a star creates Hα emission lines and Lithium absorption lines at 6708 Å, which help to identify a YSO. X-rays, another YSO indicator, are produced by magnetic activity in YSOs. Infrared excesses due to the circumstellar disk will also be seen in a YSO that still has a large amount of dust surrounding it.

Since molecular clouds span many light years, many stars form within them.
Some of these stars form in embedded clusters in the cloud. This is a useful tool in the study of astronomy. Lada et al. find that the lifetimes of such clusters are about 2-3 million years\(^2\). The dust and gas eventually clear out of the cluster and the stars can migrate out of the cluster. If the stars remain gravitationally bound, they form an open cluster.

**Goal**

The goal of this project is to use optical spectra to distinguish the young stellar objects in the sample from the field or background, derive effective temperatures and bolometric luminosities, and to estimate ages and masses for them. In order to determine YSO status, the spectra are checked for lithium absorption at 6707.8 Å and H\(\alpha\) emission at 6563 Å. Lithium is found in young stars of K and M spectral types. As the star ages, the lithium will be destroyed as it gets dragged into the center of the star by convection. H\(\alpha\) emission is found in young stars that are still accreting material from their surrounding disks. The sources were also checked for previously reported x-ray emission and infrared excesses. Effective temperatures were determined from the spectral type of the star. Spectral typing the data gives a range of temperatures for the star and then the best estimate for the spectral type and temperature is chosen from this range. Using the temperature, known magnitudes, intrinsic colors, and the distance modulus, the bolometric luminosity is derived. These values were then used to create an H-R diagram, which gives us more information about the cluster. From the theoretical isochrones and mass tracks on the H-R diagram, we can estimate the ages and masses of the stars.

**Observations**

CCD images in the B, V, and R wavelength bands were obtained with the Bok 2.3 meter telescope at Kitt Peak, Arizona in 2007. The images covered 30’ by 30’ area centered on the Serpens main cluster.

A V vs. (V-R) diagram was used to select targets for spectroscopic observation. Moderate resolution spectra were obtained at blue wavelengths using the BC Spectrograph on the Bok 2.3 meter telescope and the Hydra multi-object spectrograph on the WIYN 3.5 meter telescope at Kitt Peak, Arizona in 2008, 2009, and 2010. Moderate resolution red wavelength spectra were obtained with the same spectrographs and telescopes in 2006, 2008, 2009, and 2010, and with Hectospec on the MMT 6 meter telescope Mount Hopkins, Arizona in 2010.

**Data and Analysis**

In order to determine the spectral type of a star, the spectrum of the star must be compared with those of dwarf spectral standards. By comparing relative strengths of known absorption lines in the standard spectra, the unknown spectral type is determined. For this study on the Serpens molecular cloud, spectra were retrieved in the red and blue visual wavelength ranges, 6250 Å -7660 Å and 3900 Å -5315 Å respectively and compared to dwarf standards in the same wavelength range. The spectra were all smoothed and normalized. Many sources had spectra from more than one observation. Many sources had spectra in both the red and blue, and some had multiple red or blue spectra. These were all compared to find the best estimate for the spectral type for each source.
The red spectra had three main determining factors; the strength of the H\textalpha\ absorption line at 6563 Å, the strength of the blend absorption line at 6497 Å, and the TiO bands. The H\textalpha\ line is strongest in A stars and weakens slowly through the earlier and later type stars. The blend first appears in late A or early F stars and becomes stronger throughout later type stars. The blend surpasses H\textalpha\ in strength in early K stars as H\textalpha\ continues to weaken. The TiO band is caused by the molecule TiO and appears in later type stars. It first appears in mid K stars and strengthens throughout late K and M stars.

The blue spectra consisted of several absorption lines for comparison. He I lines can be seen only in O and B stars and disappear in later stars. The Ca II K at 3933 Å line becomes noticeable in the late B early A stars and becomes stronger in later stars. The hydrogen absorption lines, H\beta\ at 4861 Å, H\gamma\ at 4341 Å, H\delta\ at 4102 Å, and H\epsilon\ at 3970 Å are in the blue wavelength range. These lines are strongest in the early A stars and weaken in later stars. The G band is caused by the CH molecules and first appears in F2 stars, then strengthens until the mid K stars. The G band is surrounded on both sides by Fe lines. Ca I at 4227 Å appears around A5 and grows in strength until the early K stars. TiO also appears in the blue spectra of later stars and dominates by M4.5. MgH at 4780 Å appears in mid K stars and strengthens in M stars.

Giant status can also be determined through spectra via luminosity effects of certain spectral lines. In order to distinguish giants from dwarfs, a plot is created with the TiO index versus the CaH index. CaH absorption can be seen in dwarfs, but is nearly absent in giants. On this plot giant stars should be near the best fit line from the giant standards, while dwarfs will be near the best fit line for dwarf standards. YSO’s should be between these two lines.

**Results**

A total of 252 different sources were spectral typed and identified as either an association member, an extinction member, or other. Forty-four sources were identified as association members. These sources were identified by the presence of lithium absorption, H\textalpha\ emission with an equivalent width greater than 10 Å, infrared excess, x-ray emission, reflection nebula (1 source), or a combination of these. Seventy-two extinction members were objects identified as not being giants yet their luminosities and visual extinctions were too high (A(v) > 4 magnitudes) to be foreground stars if a distance of 415 pc was assumed. The remaining 136 sources were grouped as other. H-R diagrams were made by plotting the log of the effective temperature vs. the log of the luminosity for each group to determine age and mass ranges using D’Antona and Mazzitelli’s model."
In Figure 2, we see that most of the sources are young and lie above the main sequence. The one exception in figure 2 is an A star identified by infrared excess. This star lies on or above the main sequence within its error bars, which are not shown. The masses of these objects range from 0.12 solar masses to over 3 solar masses, however, most of the sources range between 0.16 and 0.70 solar masses. According to the diagram, most of these stars have a median age of $3 \times 10^6$ years.
Figure 2: H-R Diagram for extinction members in Serpens.

Figure 3 shows that all of the extinction members from our sample are above the main sequence. These sources may be pre-main sequence stars or bright background giants. According to Figure 3, the masses of these sources range from 0.2 to almost 3 solar masses. No extinction sources show up on the diagram with less than 0.2 solar masses. Most of the stars in this group show masses in the range from 0.5 to 2 solar masses. This group has a bias toward slightly more massive stars since the smaller mass stars with large extinctions are more difficult to detect.
As expected, Figure 4 shows a large scatter in both the age and mass ranges. Several sources are below the main sequence, indicating that they are actually background stars and that we have underestimated their distances. Some of the stars above the main sequence may be foreground stars.

Discussion and Conclusion

In order to learn more about star formation in general, it is necessary to make several observations in areas where we know star formation occurs. For this reason, the Serpens molecular cloud has been studied extensively. Ages and masses of individual stars in the region tell us about the star formation region as a whole. When enough YSOs have been identified as members of the Serpens cloud, we can achieve a more conclusive understanding of Serpens. This study has allowed us to identify more YSOs in that region and to determine what sources are likely to be foreground and background stars.
By determining the spectral type of the stars and calculating their luminosities, and then separating stars that met the criteria of YSOs, we were able to create HR diagrams for each group. From these HR diagrams ages and masses have been determined for our sources. According to the HR diagram for association members of Serpens, the age of the star forming region is about 3 million years and the masses of the young stars ranges from 0.12 to about 3 solar masses. From this data, we know that the Serpens molecular cloud is at least 3 million years old.

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Biography

My name is Krystal Kasal. I am a senior at UMSL, majoring in physics with an emphasis in astrophysics. I plan on going to graduate school next year. I hope to get my PhD in physics and continue doing research in the future.