Age Distributions of Low Mass Stars in the Rho Ophiuchi and Upper Scorpius Associations

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Abstract
The young star forming molecular cloud of Rho Ophiuci is an important region of study because of its proximity of 130 parsecs (425 light years). The lowest mass objects that would normally be too faint are able to studied. I compare the luminosity and temperatures of an unbiased sample of young stars in this cloud to three different theoretical models to derive ages and masses. Despite different physics in each model, the age estimates agree reasonably well. There has been some dispute as to whether the molecular cloud of Rho Ophiuchi started star formation at the same time as the nearby Upper Scorpius sub-group or subsequently. I compare the age distribution of young stars in Upper Sco to those in Rho Ophiuchi derived in exactly the same manner. New observations seem to support the theory that Upper Scorpius triggered star formation in Rho Ophiuchi.

Background
The Rho Ophiuchi (Rho Oph) cloud complex is a cluster of star-forming molecular clouds in the constellation Ophiuchus. The coordinates are right ascension of 16h 28m 06s and declination of –24d 32.5s [1]. This makes it accessible from both hemispheres. It consists of two main regions of dense gas and dust. The largest and densest, L1688, is the focus of this work. The Rho Oph complex is located at the eastern edge of the Scorpius-Centaurus OB association in the Upper Scorpius subgroup. Upper Scorpius is the youngest subgroup and has an estimated distance of 145 parsecs.

The complex is at an estimated distance of 130 parsecs (450 light years). This makes it one of the closest star-forming regions available for study. Because of this relatively close distance, low luminosity young stellar objects (YSOs) in the optical range can be viewed and studied that would otherwise would be too faint in more distant star-forming regions [2]. These YSOs can be imaged and/or spectroscopic data can be taken. It is essential to study ages and masses of young clusters to help with the overall understanding of how stars form in these regions.

Stars are formed by the gravitational collapse of a small molecular cloud of gas and dust. As the matter collapses, the cloud heats up by converting gravitational potential energy into heat. Once the cloud becomes sufficiently hot and dense, nuclear fusion will begin. During this process, the YSO is large and cool resides above the main sequence on a Hertzsprung-Russell (H-R) diagram of luminosity vs. temperature. An H-R diagram is a chart that was developed to show the link between the luminosity of a star and its temperature (also its absolute magnitude vs. spectral class). The band that appears in the
middle of the diagram is what is called the main sequence where a star spends 90% of its lifetime.

Once hydrogen fusion begins; they are no longer YSOs but main sequence stars. As these YSOs progress to the main sequence, their evolution can take them on different paths depending on the initial mass that they started with. For YSOs roughly less than 0.5 solar masses, they drop almost vertically to the main sequence, meaning they stay at the same temperature but drop in luminosity. For higher masses, they drop in temperature but stay at approximately the same luminosity as they heat up and move horizontally to the main sequence as shown in figure 2.
Luminosities and temperatures derived for the YSOs can be compared to theoretical mass tracks and isochrones to estimate ages and masses. To investigate the distribution of ages and masses in a young cluster, it is essential that one have an unbiased sample. What this means is that the sample must not be skewed toward a particular group or type of star. The YSOs from these data are complete to a visual extinction of $A_V \leq 8$ magnitudes.

**Observations**

R (650 nm) and I (900 nm) band photometry was used to select sources for spectroscopy in the 620-800 nanometer range. Of the over 270 sources observed, 135 have been identified as YSOs though the presence of Hα emission or Li in absorption in the spectra or association with X-ray emission or an infrared excess indicative of a circumstellar disk. These data were taken using the multi-object spectrograph at the Blanco 4 meter telescope at CTIO and the WIYN 3.5 meter telescope at KPNO.

**Reduction & Analysis**

Spectral types were determined by comparing our spectra to a set of dwarf star standards. Spectral types were then converted to effective temperature. In order to determine the luminosity of a star, the data must be corrected for reddening and the extinction by foreground dust must be determined. Because these YSOs are embedded inside the cloud, the gas and dust absorbs much of the light. The extinction coefficient, $A_V$, accounts for this absorption. The equation that was used for the computation of $A_V$ is as follows:
\[ A_v = 4.7 \times [(R-I)_{\text{observed}} - (R-I)_{\text{intrinsic}}] \]

where \((R-I)_{\text{intrinsic}}\) is determined by the temperatures of the star. The absolute I band magnitude and luminosity over all wavelengths could then be determined.

The data was then processed through three different stellar evolutionary models; D’Antona and Mazzitelli (1997, DM97), Siess, Dufour, & Forestini (2000, SDF00) and Palla and Stahler (1999, PS99). All three models yield the log of both the luminosity and the temperature as a function of the mass and age of the young star. While the models output the same categories, they differ in some significant ways. The models use slightly different theories for the stellar atmospheres as well as the internal dynamics of the star. Also, the PS99 and SDF00 models do not go down the very low mass stars, less than 0.1 solar masses. DM97 however is capable of reaching down to stars as low as 0.02 solar masses \cite{ref1, ref2, ref3}. The three models were incorporated into a program called trax. Eric Mamajek from the University of Rochester wrote the trax program in the FORTRAN computer language. This information was then put in a histogram using the log of both the age and the mass.

**Results**

In general, the models agreed relatively well with each other. While the focus of this work is the ages of the sources, the mass results deserve a mention. All three models peaked in the same bin for the mass; however, both SDF00 and PS99 leaned toward the heavier masses, which reflect the differences in the models regarding the internal dynamics of the star.

There are differences between in the results in relation to the age. Using the R-I color, all three models peaked in the same bin of 6.5. The SDF00 and PS99 models were weighted toward older ages (fig. 3), especially SDF00. The log of the average age in the DM97 models of the 135 sources was calculated at 6.49±0.05, which is about 3.1 Myr. The I-J data set was abandoned because the data were not simultaneous. It should also be noted that using the I-J color magnitude, the DM97 model peaked in bin 6.5 while SDF00 and PS99 both gave a slightly younger age distribution in the 6.0 bin.
The data from L1688 was also compared with the population of 252 sources from Upper Scorpius (Upper Sco). Upper Sco is an OB subgroup in the vicinity of Rho Oph, all part of the Scorpius-Centaurus OB association. The purpose of comparing these two regions is to see how the formation of the young stars may be similar or related, if at all. Both samples were de-reddened using J-H data from the Two Micron All Sky Survey (2MASS). This was done to ensure the luminosities were derived in exactly the same way using the same color magnitude. J-H was used, as data for Upper Sco was only available in J-H color. Sources were dereddened using

$$A_v = 9.1 \times [(J-H)_{\text{observed}} - (J-H)_{\text{intrinsic}}]$$

The data were then uploaded into the trax program and analyzed in the same method as the R-I data described earlier.
Figure 4. Log(age) histogram of Rho Oph using J-H

Figure 5. Log(age) histogram of Upper Sco using J-H
According to the histograms, the YSOs in L1688 no longer peak at the same age but DM97 and PS99 yield younger ages relative to SDF00 and relative to ages derived using the (R-I) color. An average age of 6.14±0.05 (1.3 Myr) is obtained from the DM97 models. The reasons for the younger ages are not well understood but could involve the reddening law or excess emission in the H band from circumstellar dust. For Upper Sco, the three stellar evolutionary models agree very well with each other. They all peaked in the same bin and once again, the SDF00 and PS99 models are skewed toward the older ages as seen in figure 5. The log of the average age for Upper Sco is calculated from the DM97 models at 6.43 (2.6 Myr). This is younger than the age of 5 Myr generally assumed for this region.

Comparing the histograms from the two regions, a relationship can be suggested. However depending on the model used, that relationship would be quite different. The SDF00 model suggests that both Rho Oph and Upper Sco began star formation at approximately the same time. This could be the result of an external shockwave affecting both clouds simultaneously.\textsuperscript{[2]}

On the other hand, DM97 and PS99 models suggest that star formation started in Upper Sco first, then spreading to Rho Oph. The overall picture of star formation history of the Scorpius-Centaurus OB association can be seen in the illustrations below. It all started in the Upper Centaurus-Lupus subgroup (outside of Upper Sco and Rho Oph). A large shockwave was created when the most massive star in Upper Centaurus-Lupus exploded as a supernova. This shockwave passed through the Upper Sco and triggered the star formation process, as in figure 6A. The most massive stars in Upper Sco began to disperse the molecular cloud in (6B). The most massive star in Upper Sco exploded as a supernova (6C), which fully dispersed the cloud in Upper Sco, and passed through the Rho Oph cloud, where it could have started star formation there (6D).\textsuperscript{[8]}
The data analysis of this paper supports this overall view of how star formation began in Rho Oph. However, our data does not agree with the absolute time frame presented in earlier papers and in figure 6 between the ages of Upper Sco and Rho Oph.

**Summary**
The YSOs in the molecular cloud Rho Ophiuchi appears to be younger than the population in the Upper Scorpius subgroup. There is a discrepancy of 2.2 Myr between the average ages depending on the color used to derive extinction. Perhaps the reddening law must be modified for the (R-I) or (J-H) band. Also, R-I data for Upper Sco would be helpful to determine if the estimated age difference is the same as the J-H. However, since the data for both associations are calculated in the same way, the J-H data supports Upper Sco triggering star formation in Rho Oph, not a shockwave hitting both clouds simultaneously from another source.

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**References**

**Biography**

John Keller is a senior at the University of Missouri – St. Louis. He had spent 14 years in the private sector working construction and in the shipping/logistics industry as a supervisor. After the elimination of his department during a merger, he decided to leave corporate life to pursue a degree. Astronomy and physics was a subject he had always maintained an interest in and enjoyed. In addition to a student, he is a stay at home dad and manages a rental property. He is a St. Louis native and lives in Shrewsbury, MO with his wife of ten years and two year old son.