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PARTIALLY EMBEDDED YOUNG STELLAR AGGREGATES

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RESUMEN

Resumimos los resultados obtenidos durante el último año, sobre la ubicación en el diagrama H-R de estrellas de pre-secuencia principal en grupos estelares jóvenes en las nubes moleculares L1641 y ρ Oph y sobre la estimación de las edades relativas de estos grupos y su contribución a la formación estelar global en las nubes moleculares donde se encuentran.

ABSTRACT

We summarize the results obtained over the last year in placing pre-main sequence stars in young stellar groups in the L1641 and ρ Oph molecular clouds in the H-R diagram, and in assessing the relative ages of these group and their contribution to the overall star formation in the molecular clouds where they are found.

Key words: **STARS: FORMATION — STARS: PRE-MAIN SEQUENCE — INFRARED: STARS — HERTZSPRUNG-RUSSELL DIAGRAM**

1. INTRODUCTION

In the past few years it has become apparent that star formation in dark clouds occurs in moderate size groups (10–50 stars) as well as in rich "clusters" (Gómez et al. 1992; Strom, Strom, & Merrill 1993). When very young, these groups are more easily identified from imaging surveys in the near infrared where some of the embedded population can be seen. With reasonable assumptions, we are able to study the luminosity functions of these embedded groups and to infer age and mass distributions and the frequency of accretion disk occurrence within the aggregates before the peculiar motions of the stars carry them away from their birthplaces. Using these techniques we were able to show that, in L1641 (Strom, Strom, & Merrill 1993); 1) the stars in the aggregates are younger than the stars dispersed through the cloud, 2) the stars within the aggregates exhibit a higher disk frequency than the stars in the distributed population, and 3) the IMF appears similar to the solar neighborhood IMF discussed by Scalo (1986).

However, these results are based on analysis of reddening corrected infrared luminosity functions. We cannot construct H-R diagrams until we have spectra of the individual objects. I will report on the progress in the last year toward this goal.

2. OBSERVATIONS

We obtained red spectra in regions centered on the L1641 South Cluster and on the L1641 North aggregate as well as other regions in L1641 using the Hydra fiber fed bench spectrograph on the 4 meter telescope at Kitt Peak. These spectra covered the region from just shortward of the Na I D lines to $\sim$ 9 000 A with a resolution of $\sim$ 5 A. We also obtained spectra with the same parameters for a large number of proper motion members of 1) h and χ Per, defining the upper main sequence, 2) M67, defining the mid-main sequence and the subgiant branch, and 3) Praesepe, defining the lower main sequence, from F2 to M4. Beyond M4 we used the spectra of Kirkpatrick et al. (1991) for our standards.

At this point we have classified the spectra for the stars in L1641 North and L1641 South. We will use these data, combined with our optical and near infrared photometry to place these stars in the H-R diagram.

3. PROCEDURE

In order to place stars in the H-R diagram, we require an effective temperature and a luminosity. The spectral types are sufficient in themselves to define the effective temperatures for the stars. The luminosities are more difficult since they require us to determine reddening corrections and to apply bolometric corrections. We also have the problem, for pre-main sequence stars, of finding the proper wavelength at which to measure the photospheric flux since disk emission, from both reprocessed radiation and accretion luminosity in the infrared, and from boundary layer emission in the visible affects the object colors. The region of the spectrum least contaminated by these effects lies in the I and J bands, 8 000 A to 1.3 μm (Bertout, Basri, & Bouvier 1988; Hartigan et al. 1992). We choose to use the J (1.25μm) magnitude because 1) the bolometric corrections vary slowly and monotonically at this wavelength and 2) the extinction corrections are minimized. We measure the extinction to each star by the excess in the $(R-I)_c$ color, using the Bessell & Brett (1988) standard main sequence colors as our unreddened colors. With this information, the distance modulus, and the bolometric magnitude of the Sun, we can then compute the reddening corrected stellar luminosities.

4. THE L1641 NORTH AGGREGATE

The L1641 North aggregate was discovered by Strom, Margulis, & Strom (1989) and has since been studied by Chen et al. (1993) and Hodapp & Deane (1993). The compactness of this group and the high extinctions found made impossible the obtention of a significant number of spectra with Hydra in the two pointings we obtained. However Hodapp & Deane have obtained spectra in the 2μm region within this group. Therefore, we have available within the cluster core 4 spectra from Hydra and 11 infrared spectra. Over a larger area, for the 13 stars with spectra from both studies, the agreement is excellent, $\pm$ 1 subclass. We have used the combined set of spectral types and our optical and near infrared photometry to place these stars in the H-R diagram. For those stars too obscured to obtain an $(R-I)_c$, ($^1/_3$ of the sample), the extinction was estimated from the $(J-H)$ color. The masses in the spectroscopic sample range from 1 $M_\odot$ to the hydrogen burning limit. The age, as estimated from the tracks, is $\lesssim 3\times10^5$ yr. The largest A_v value for the spectroscopic sample is 18 mag.

This H-R diagram permits us a rare look at a group of extremely young stars in the process of dispersing into the general cloud population. The PMS evolutionary tracks are taken from D'Antona & Mazzitelli (1994). The distribution shown on the right side of the figure is the reddening corrected luminosity function for the spectroscopic sample. The longer line represents a best guess for the luminosity of a continuum + emission star which could not be placed in the H-R diagram. The open circles are objects seen only via reflected light (i.e., reflection nebulae) and their luminosities are therefore minimum luminosities.

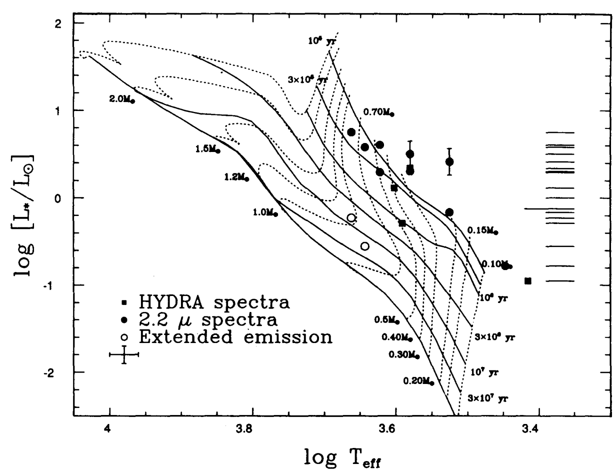

Figure 1. The H-R diagram for the L1641 N aggregate.

5. THE L1641 SOUTH CLUSTER

Almost 2° farther south in the L1641 cloud a new young cluster was discovered (Strom, Strom, & Merrill 1993) in the course of this study. We have obtained spectra of 27 stars within this more populous group.

The H-R diagram derived for this cluster shows that it is clearly older than the L1641N aggregate, by a factor of 2–3.

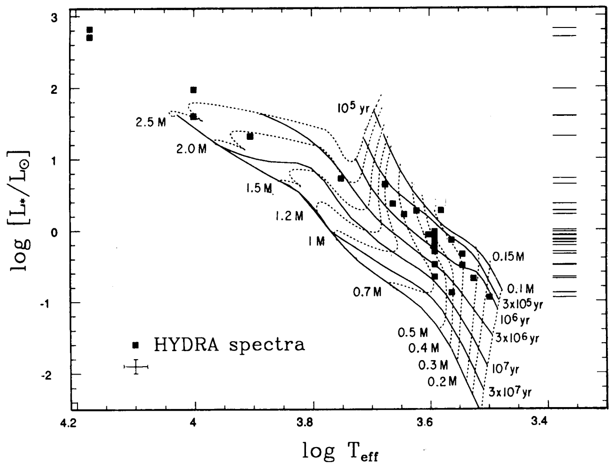

Figure 2. The H-R diagram for the L1641 South cluster.

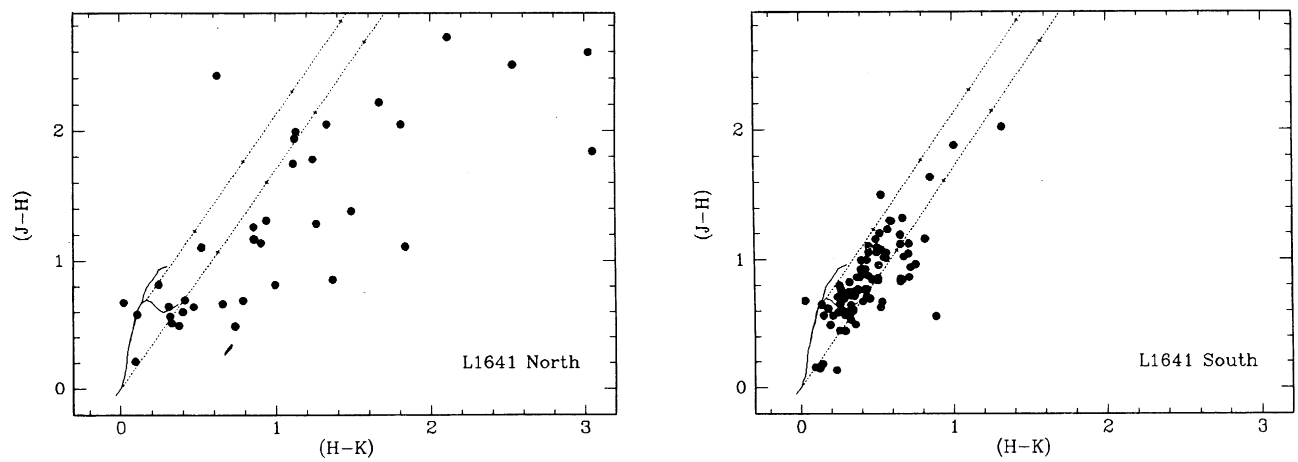

Figure 3. The infrared color-color diagrams for the L1641 North and L1641 South groups.

The color-color diagrams also show a decrease in the frequency of objects showing extreme disk characteristics (i.e., those objects lying to the right of the reddening lines). The tick marks on the reddening lines show 5 magnitude intervals in A_v.

The initial mass function inferred from this data is consistent with the Scalo (1986) IMF found from the solar neighborhood stars.

6. THE ρ OPH CLOUD CORE

Over the last decade there has been considerable study of the ρ Oph dark cloud, both from investigation of the embedded stellar population and its possible future as a bound cluster, and from mapping of the clump structure of the molecular cloud. Recent studies with the VLA of the population of PMS objects that are strong radio sources in the cm wavelength domain, may provide us with a window on stellar aggregates at a yet younger age. The VLA survey of Leous et al. (1991) shows that the radio sources are significantly clumped and associated with the ρ Oph A & E/F cold dense cores mapped by Loren, Wooten, & Wilking (1990) in DCO^+. Other sources are associated with the ρ Oph B core, which has not yet been deeply searched. In general these sources exhibit thermal radio spectra most likely from free-free emission from the ionized wind. One of these VLA sources is the highly collimated outflow source VLA 1623–243 (André et al. 1990).

In order to learn more about the properties of these extremely young objects, we recently obtained colors from $1.25\mu m \rightarrow 4.8\mu m$ for 18 of these objects and upper limits for another 8 at K and L. These objects are extremely red and compare well with the colors of Class I objects and well-known sources driving powerful outflows and having either optical or radio jets. It appears that there are possibly 3 dense stellar aggregates of extremely embedded "protostars" within the ρ Oph Cloud, probably driving outflows which may be difficult to detect either because they are 1) extremely compact or 2) confused due to the density of driving sources.

There is a large distributed population in the ρ Oph Cloud also. The near infrared color-color diagrams clearly show the differing disk frequency between the core and the distributed population. The H-R diagram of the distributed population shows that the ρ Oph Cloud has been producing stars for $\sim 3 \times 10^6$ yrs.

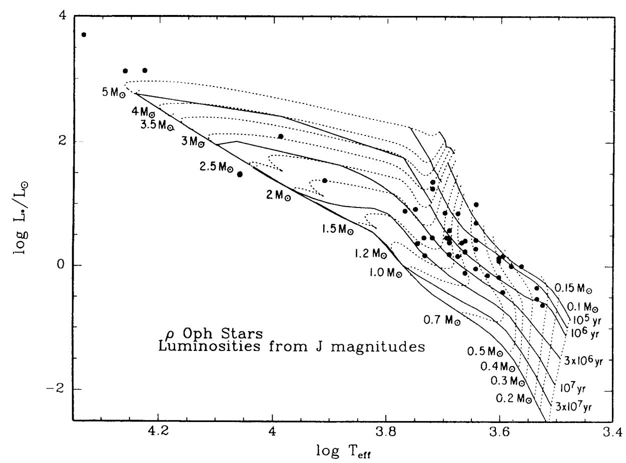

Figure 4. The H-R diagram for the distributed population in the ρ Oph molecular cloud.

7. CONCLUSIONS

1. The (partially) embedded stellar aggregates appear to be very young. ($t < 10^6$ yr).
2. They exhibit a small range in age.
3. They exhibit a very high disk frequency, $> 50\%$.
4. They appear to exhibit an IMF characteristic of the local solar neighborhood.

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DISCUSSION

Rodríguez: Did you say that the objects in the "ring" are reflection nebulae? Is there an explanation for their characteristics?

K. Strom: It is definitely true that a large fraction of those objects are extended with sizes on the order of a few arcseconds. This has been confirmed by high spatial resolution observations with the *IRAS*. We have no infrared spectra of any of these objects yet, so we do not know for certain that these are not emission nebulae, possibly due to shock excitation.

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