DISCOVERY OF THE σ ORIONIS CLUSTER

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ABSTRACT.
We report the discovery of a clustering of young low mass stars in the vicinity of σ Orionis. The region is rich in X-ray sources. Followup optical spectroscopy shows that most are low mass pre-main sequence (PMS) stars. Using multi-object spectroscopy and wide-field CCD imaging, we have mapped the square degree surrounding σ Orionis. In the immediate vicinity of σ Ori we find

- over 80 X-ray sources positionally coincident with bright stars ($10<V<16$).
- over 100 low mass PMS PMS stars identified from spectroscopy.
- a clustering of the PMS stars, with an inferred spatial density of 700 stars/deg^2.
- a clearly defined PMS locus, with an age of 2 Myr, ranging from V=10 down to V=19.

This cluster may be an older analog of the Orion Nebula Cluster. We will discuss the properties of these stars, and implications for the early evolution of dense clusters.

1. Introduction

For many years, the conventional wisdom had been that low mass stars simply did not form in regions of high mass star formation. Those regions which form low mass stars, the T associations, were dominated by the classical T Tauri stars (cTTS), stars noteworthy for their strong Hα emission, their UV and IR continuum excesses, and their erratic variability. It was obvious that there were no high mass stars in T associations[1]. But in OB associations, any low mass stars would be masked by selection effects, lost in the glare of the far brighter of the far-brighter O and B stars, so to speak. Theory suggested that star formation was bimodal, and that high mass and low mass stars formed by different processes (e.g., Larson 1986; Shu & Lizano 1988). There was no reason to expect there to be significant numbers of low mass stars in OB associations.

However, for years evidence to the contrary has been accumulating. In Orion, Haro (1953) noted the existence of many emission-line objects in the vicinity of the Orion Nebula. Walker (1969) obtained spectra of a number of these stars, and showed that they were members of the ONC and hence were pre-main sequence stars. Andrews (1981) published a photometric atlas of Orion showing the existence of many dM stars that were likely PMS stars. Hillenbrand (1997) has reported on a detailed photometric

[1] See Walter & Boyd (1991) for a different point of view.

and spectroscopic analysis of the low mass population in the inner 2.5 pc of the ONC. There have been spectroscopic studies of the G stars in Orion OB1c, just outside the Orion nebula (e.g., Smith et al. 1983). Strom et al. (1990) have discussed the low mass population of the L1641 cloud, to the south of the ONC.

On the other side of the sky, Walter et al. (1994) used an X-ray-based search to look for the low mass population of the Upper Sco OB association (de Geus et al. 1989), and found 28 low mass PMS stars in 7 deg^2 of the association. After correcting for the incompleteness of the X-ray sampling, they concluded that the association has a field star mass function between about 0.2 and 10 $M_\odot$. The total number of low mass stars (<2 $M_\odot$) is about 2000. Part of the reason that this enormous population of low mass stars lay undetected is that few of the stars are cTTS: most have lost their circumstellar disks, perhaps because of the influence of the winds and ionizing flux of the B stars, or because of supernovae in the association.

The detection of this low mass population in OB associations, and characterization of the stellar properties would serve a number of purposes:

- The low mass stars may give a better picture of the history of star formation in OB associations. The locations of low mass stars in the H-R diagram are far more sensitive to age than are the positions of the ZAMS B stars.

- We can study the clustering of low mass stars in the vicinity of the most massive members of the association. Do the low mass stars form a smoothly distributed backdrop to the OB stars, or does each massive star form with associated low mass stars, as appears to be the case in the Orion Nebula?

- The low mass stars may give a better picture of the kinematics of OB associations. If there is mass-segregation, it will be revealed by the low mass stars. Radial velocities are more easily measured for the (narrow-lined) low mass stars, which have numerous sharp lines, than they can be for the B stars.

- Since most low mass stars form in OB associations, not T associations, extrapolations from stars in T associations may be misleading. In OB associations, the external influences of the high mass star's winds and ionizing radiation (not to mention supernovae) may destroy accretion disks, altering the mass function, and affecting the binary fraction and the formation of planets.

We have been studying the low mass population of the Orion OB1 association, exclusive of the Orion Nebula (Obi OB1d). Here we report on our initial results in the vicinity of σ Ori, the uppermost star in Orion's sword, hanging below ζ Ori on the east side of the belt of Orion. σ Ori is a member of the Ori OB1b association, which consists of about 126 B stars with an age of about 2 Myr at a distance of about 380 pc (Brown et al. 1994). σ Ori is a trapezium system, with 5 bright members. The A component (O9.5V) and B componment (B0.5V) are a visual pair with a 170 year orbit. Component C (A2V) is at 11 arcsec; components D and E are both B2V, at distances of 13 and 42 arcsec, respectively (Hoffleit 1964).

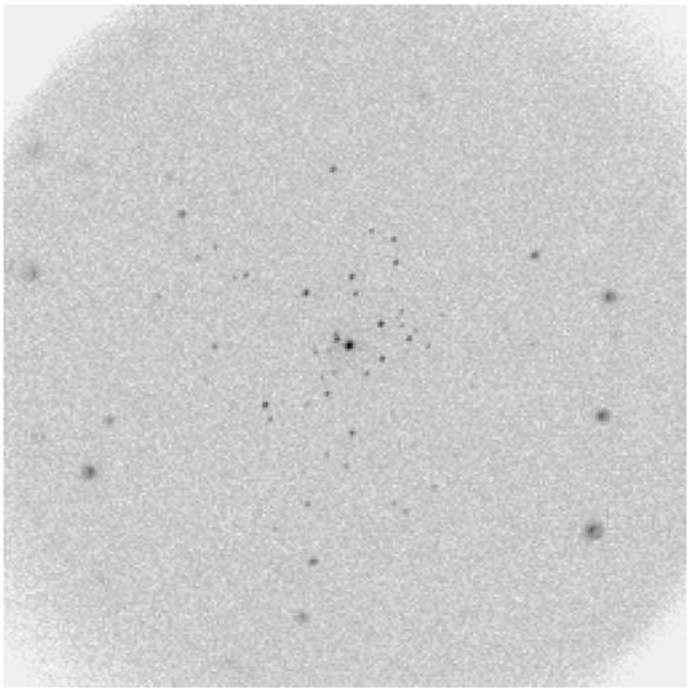

Fig. 1. The ROSAT HRI image of σ Orionis. This is the sum of 31 HRI observations amounting to 76 ksec of observing time. The region plotted is 34 arcmin across. The image is logarithmically scaled; the bright source in the center is σ Ori.

2. The Observational Data

The σ Ori region has been observed by ROSAT on a number of occasions. The data consist of a 36 ksec PSPC observation (WP201151) plus about 76 ksec of HRI data in 31 images (Figure 1). The X-rays from σ Ori itself have been discussed by Berghöffer & Schmitt (1994). About 100 other X-ray sources lie within 1 degree of σ Ori. The initial source lists were compiled from SASS standard processing. Many of these sources have optical counterparts.

The optical image, shown in Figure 2, is dominated by σ Ori (V=3.8). We obtained multi-object spectroscopy and wide-field photometry of this region.

Spectroscopy: We obtained spectra of some counterparts with the KPNO 2.1m GOLD-CAM (1992-1995). In the winter of 1995-1996 we obtained 4 observations of this field using the WIYN/HYDRA, as part of the KPNO queue scheduling program. We observed the optical counterparts of the X-ray sources as well as a randomly-selected sample of stars in the HST Guide Star Catalog (GSC).

In all, we obtained useful spectra of about 300 stars. Among these, we identified 104 likely pre-main sequence (PMS) stars spectroscopically within 30 arcmin of σ Ori.

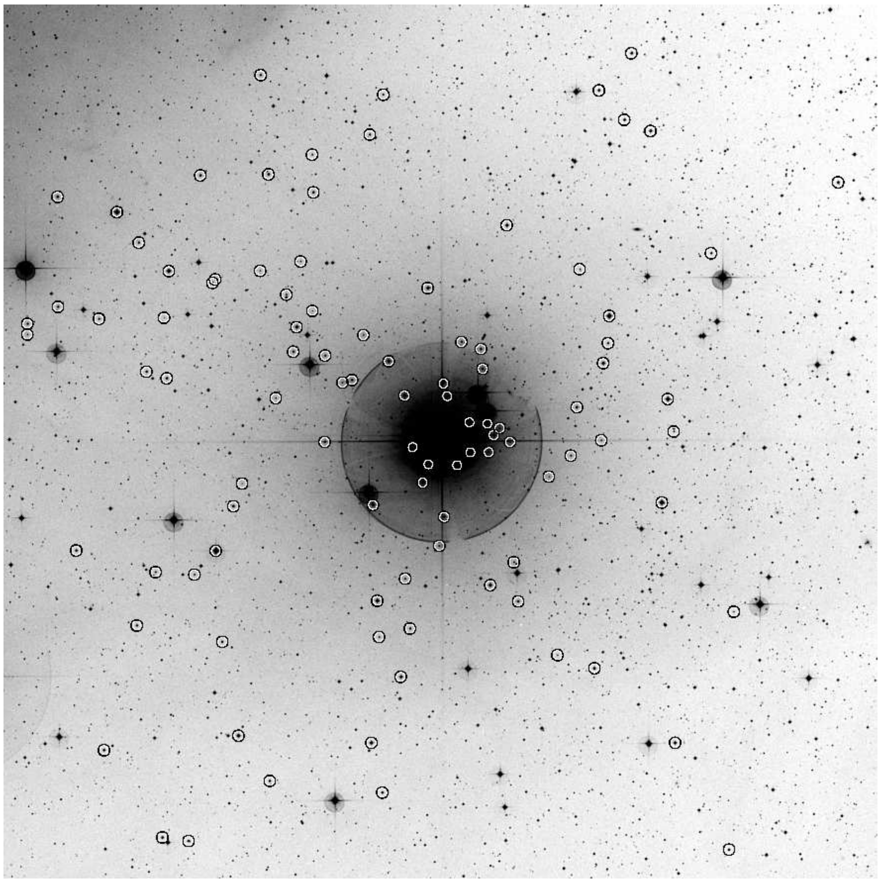

Fig. 2. The optical image of σ Orionis, taken from the Digital Sky Survey. The region is 30' × 30' across. Spectroscopically-identified low mass pre-main sequence stars are circled.

Primary identification is made on the basis of a strong Li I λ6707Å absorption line. For stars with low S/N spectra, where we cannot unambiguously detect Li, Hα emission is used as a proxy indicator (at the expense of including some foreground dMe stars and some stars with improper sky subtraction). Hα strengths range from an emission equivalent width of 77Å in a K1 star to apparently normal photospheric absorption. We also use radial velocities as a further membership criterion (see below).

Typical spectra are shown in Figure 3. Of these 104 likely PMS stars, 28 (27%) are not X-ray sources. 258 of the optical stars we observed are taken from the HST Guide Star Catalog. While some of these are X-ray sources, many are not, and were selected solely because of their good optical positions to fill otherwise unused fibers on the Hydra spectrograph. These stars constitute a magnitude-limited sample of stars unbiased with respect to either activity or color.

Of the 258 stars in the GSC which we observed, 57 (22%) are likely PMS. This is an unbiased sample, subject only to to the incompletenesses in the GSC. Assuming

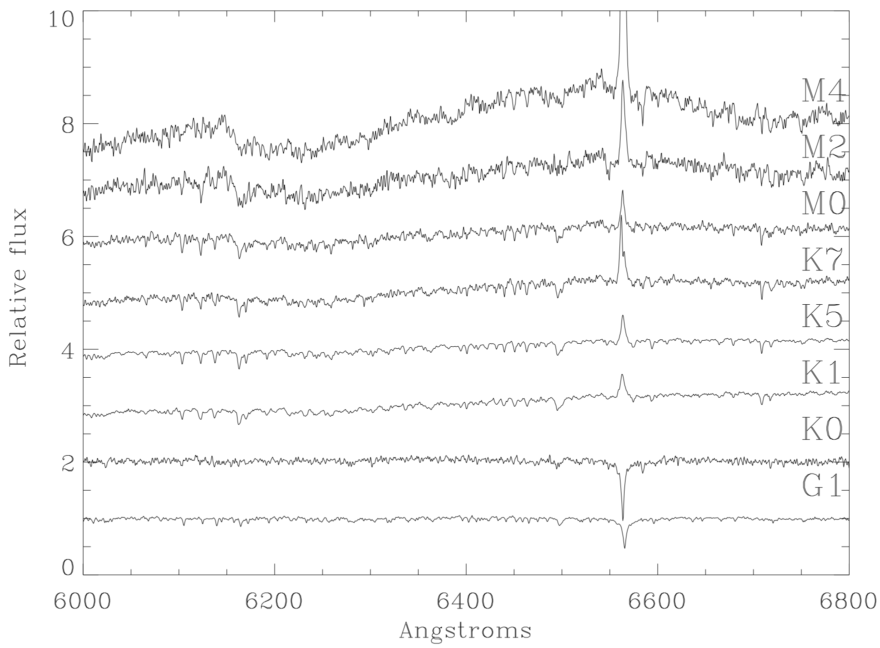

Fig. 3. Spectra of 8 typical PMS stars near σ Ori, ordered by spectral type. Spectra are scaled to a mean of 1, and offset by 1 unit from each other. The K0 star is a double-lined spectroscopic binary.

completeness to V=14, we estimate the space density of PMS stars with 10<V<15 within 30 arcmin of σ Ori to be 120 stars per square degree.

We determined radial velocities by cross-correlating the spectra with spectra of the dusk or dawn sky. At this fairly low dispersion (1-2Å resolution), uncertainties are about ± 5 km s^{-1} for spectra with high S/N. Uncertainties are larger for spectra with lower S/N, and for M stars. The distributions of radial velocities are shown in Figure 4. The narrowness of the radial velocity distribution confirms that the stars are members of the Orion OB association.

Photometry: We took UBVRI images at the CTIO 0.9m in January and February 1996. While we only imaged 0.15 deg^2, the sampling is complete to V=19, except in the immediate vicinity of σ Ori. The color-magnitude diagram (Figure 5) shows a clear PMS locus, well separated from the background galaxy. In addition to the 45 PMS stars identified spectroscopically (for which we have photometry), there are another 65 other stars along the isochrone to V=19. Most are likely to be PMS stars. These 110 photometric PMS stars imply a space density, 12<V<19, of about 700/deg^2 (If you believe all stars are born binary, double this number!).

The GSC PMS sample shows evidence for clustering, both spatially and in velocity. The distribution of radial velocities (Figure 4) is consistent with a single velocity (at

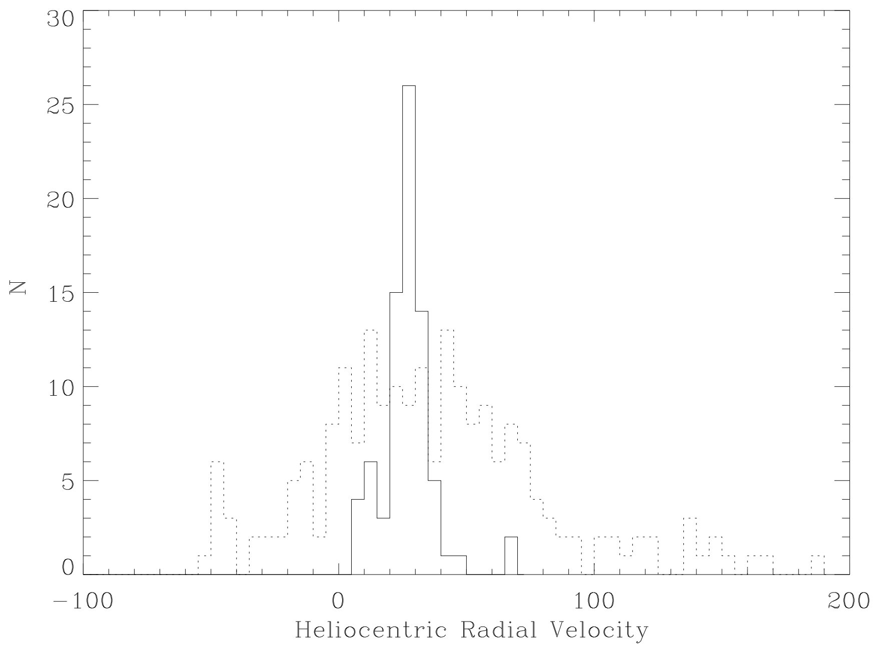

Fig. 4. The distribution of radial velocities of the stars in this sample. The spectroscopically-identified PMS stars (solid histogram) are well-fit as a Gaussian distribution of mean 25 km s^{-1} with σ=5 km s^{-1}. The secondary peak at 12 km s^{-1} is due to a systematic shift of M star velocities, and may be an artifact of using a sky spectrum as a velocity template. The radial velocities of the other stars in the sample (dotted histogram) have a mean of 31 km s^{-1} with σ=37 km s^{-1}.

least for the G and K stars) with a velocity dispersion 5 km s^{-1}. As this is about the resolution of our spectra, the intrinsic velocity dispersion must be less, as one would expect from a physical cluster.

The centroid of the spatial distribution of the PMS stars is centered on the position of σ Ori. We summed the PMS stars and the other GSC stars into radial bins centered on σ Ori (Figure 6). While the distribution is flat for the non-PMS stars, the radial distribution of the PMS stars is indeed peaked. The inferred cluster radius (where the density of PMS stars reaches zero) is about 0.5 deg (3.3 pc).

3. Caveats and Conclusions

It is important to stress that the results reported here are preliminary, and that the analysis is continuing. However, the basic conclusion is secure: there is a significant population of low mass PMS stars in this region. The stars appear to cluster spatially around σ Ori. We claim the discovery of the σ Orionis cluster (where cluster is loosely defined, and not intended to imply a gravitationally-bound group).

The narrowness of the PMS locus suggests coevality, at the 2 Myr age of the OB

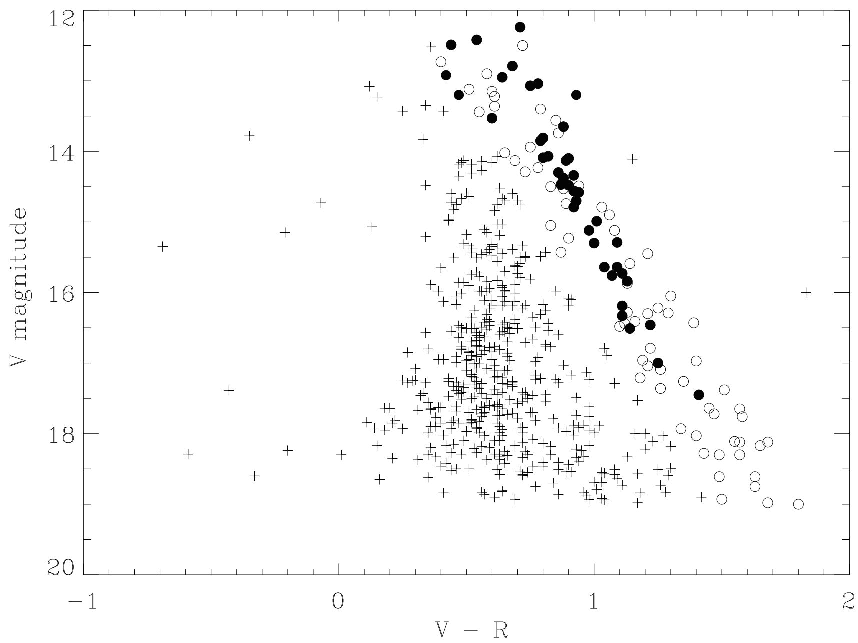

Fig. 5. The observed color-magnitude diagram for stars with 12<V<19 in the 0.15 deg^2 we observed within 15 arcmin of σ Orionis. Spectroscopically-identified low mass pre-main sequence stars, marked with solid circles, define the PMS locus. Photometric PMS candidates are indicated by the open circles. These data are not corrected for extinction; the reddening vector parallels the PMS locus.

association. The total inferred mass of this group of stars is comparable to that of the Orion Nebula cluster (ONC). We suggest that this is an evolved analog of the ONC. This is the *second youngest* cluster now known, after the ONC. The cluster is unobscured by gas and dust, and offers the opportunity to study the very early evolution of low mass stars in a high mass cluster environment.

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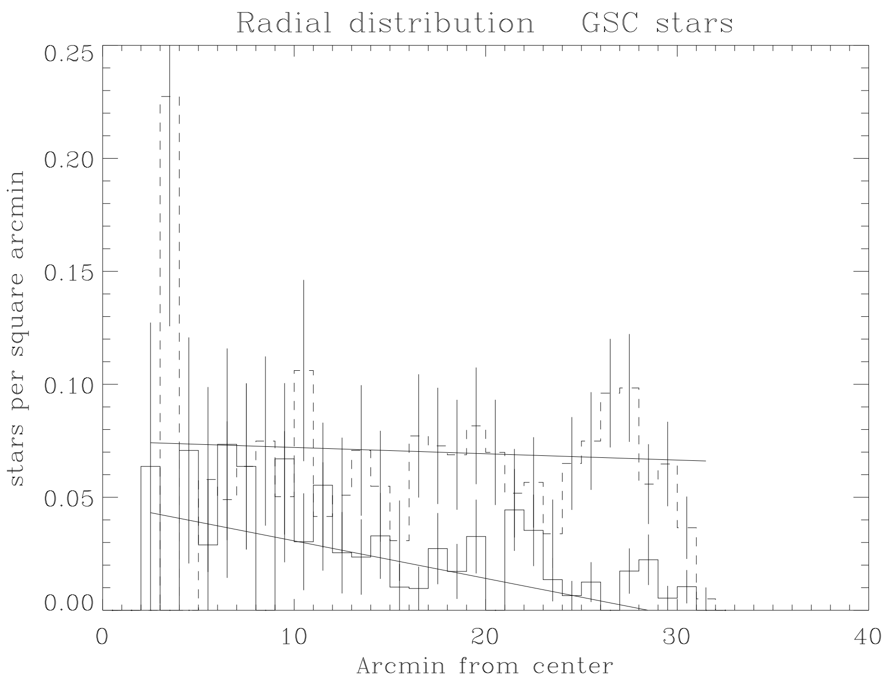

Fig. 6. The radial distribution of stars in the GSC sample. PMS stars (solid histogram) show a clustering towards σ Ori, while other stars in the GSC (dashed distribution) do not. The probability that the two samples are drawn from the same parent distribution is 0.0003. The lines are linear least-squares fits to the distribution. The lack of stars within 3 arcmin is an artifact of the glare from the V=3.8 star.

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