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THE INITIAL MASS FUNCTION IN THE RHO OPHIUCHI CLUSTER

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ABSTRACT

Approximately 20 arcmin^2 in the Rho Ophiuchi cloud were imaged deeply at 2.2 μm. No new sources were found down to a completeness limit of $m_K = 14.5$. We conclude either that the low-mass sources have radically different infrared spectra than higher mass ones or that the initial mass function levels out or turns over near a few tenths of a solar mass, and that the formation of very low mass stars and substellar objects is suppressed. If this latter result is true generally, large substellar objects cannot contribute significantly to the "missing mass."

Subject headings: infrared: spectra — stars: formation

I. INTRODUCTION

What is the form of the stellar initial mass function at the bottom of the main sequence? Does it rise with decreasing mass, signalling a numerous population of brown dwarfs as a major constituent of the universe? These questions have been difficult to answer because low-mass stars emit only a miniscule fraction of their already small luminosities in the optical, and hence are selected against in many optical searches. For example, as summarized by Rana and Wilkinson (1987), different investigators disagree on the space density of 0.1 $M_\odot$ stars by nearly an order of magnitude.

At least two important issues hang on the resolution of this matter. First, the structure of the initial mass function will help reveal the nature of the fragmentation processes that lead to star formation in interstellar clouds. Second, the missing mass in the Galactic disk may or may not be composed of very low mass stars and substellar objects, depending on the shape of the IMF; recent papers have suggested that the evidence is consistent with (D'Antona and Mazzitelli 1986) or against (Larson 1986) this hypothesis.

Infrared measurements are sensitive to the true luminosity of very low mass stars and are therefore capable of unbiased searches. D. W. McCarthy and collaborators have used one-dimensional infrared speckle interferometry to find very low mass compansions to many nearby stars (e.g., McCarthy *et al.* 1988); their results suggest that the number of very low mass, very close companions has been underestimated by previous searches. The advent of infrared arrays promises to make a broader variety of unbiased searches feasible.

The Rho Ophiuchi molecular cloud has many advantages for such searches. It is relatively nearby (160 pc; Wilking, Lada, and Young 1989 and references therein), making very low luminosity objects detectable. Extensive studies show it to contain an embedded cluster of young age $\sim 3 \times 10^6$ yr), low-luminosity, low-mass stars (e.g., Fazio *et al.* 1976; Young, Lada, and Wilking 1986). A reasonable presumption is that conditions would be as favorable as possible for the presence of objects of still lower mass and luminosity. The region has been extensively mapped in the near-infrared (see summary in Wilking, Lada, and Young 1989), and some areas have an exceptionally high density of objects. These relatively small regions of most active star formation are the most attractive for further mapping to greater depth, since one could expect to detect many more stars if very low luminosity ones are abundant. This *Letter* reports a preliminary exploration of one such region.

II. OBSERVATIONS

The data described in this *Letter* were obtained between 1988 May 31 and June 4, with the 64 × 64 pixel HgCdTe camera described by Rieke, Rieke, and Montgomery (1987). This instrument was mounted on the Steward Observatory 2.3 m telescope, and its pixel scale was set to 0$''$.85, giving a total field of view of 54$''$. A K (2.2 μm) broad-band filter defined the spectral response, and the on-chip integration time was set to fill the CCD wells to about 70% of capacity. Because the ambient temperature varied substantially during the telescope run, actual integration times varied to reach this limit. After the first readout of the array, the telscope was wobbled to a point on the sky 51$''$ north; after the second readout, it was returned to the original position. These two directions were alternated to provide coverage of a 54$'' \times$ 102$''$ rectangle in the pairs of frames. Observations were continued to allow reliable detection of sources down to $m_K = 15$ (roughly 5 standard deviations). After one such rectangle had been observed, the telescope was offset to a new position and the observing procedure repeated.

The area surveyed is centered on the bright source EL 29, for which we assumed the position $16^h24^m07^s.8$, $-24°30'33''$ (1950). This object was readily visible on the real-time display of the camera, and it was used as a positional reference. We offset the

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TABLE 1

FRAME CENTER COORDINATES

R.A.	Decl.
16ʰ24ᵐ13ˢ1..........	−24°27′39″
16 24 13.1..........	−24 26 48
16 24 09.6..........	−24 27 39
16 24 09.6..........	−24 26 48
16 24 06.1..........	−24 27 39
16 24 06.1..........	−24 26 48
16 24 13.1..........	−24 29 19
16 24 13.1..........	−24 28 28
16 24 09.6..........	−24 29 19
16 24 09.6..........	−24 28 28
16 24 06.1..........	−24 29 19
16 24 06.1..........	−24 28 28
16 24 13.1..........	−24 30 59
16 24 13.1..........	−24 30 08
16 24 09.6..........	−24 30 59
16 24 09.6..........	−24 30 08
16 24 06.1..........	−24 30 59
16 24 06.1..........	−24 30 08
16 24 02.6..........	−24 30 59
16 24 02.6..........	−24 30 08
16 23 59.1..........	−24 30 59
16 23 59.1..........	−24 30 08
16 24 13.1..........	−24 32 39
16 24 13.1..........	−24 31 48
16 24 09.6..........	−24 32 39
16 24 09.6..........	−24 31 48
16 24 06.1..........	−24 32 39
16 24 06.1..........	−24 31 48

telescope from EL 29 according to the telescope dial readings to reach the other positions. Tracking was verified by returning to EL 29 during interruptions of the integration sequence.

Table 1 shows the positions observed. The extinction map of Wilking and Lada (1983) shows that the total obscuration through the cloud at all these positions is 8 mag or more at K; to be detected at our limit of $m_K = 15$, a background source would need to be at an intrinsic $m_K < 7$, or assuming typical field star colors, $m_V < 10$. In the ~ 20 arcmin^2 surveyed, finding such a bright star would be quite unexpected (over the whole sky, they are at a density of roughly 1 per 4000 arcmin^2). A deep CCD frame at I centered on EL 29, obtained on the KPNO No. 1 0.9 m telescope, shows that the region is free of sources (with a single exception) to an I mag of >19. Hence, foreground sources are also not a concern, and we can safely assume that any objects detected in the survey are associated with the young stellar cluster embedded in the Ophiuchus cloud.

To reduce the data, we averaged and ratioed the pairs of frames taken at the two wobble positions of the telescope. Sources in the southern frame of the pair then appear as positive objects, while those in the northern appear as negative ones. Source crowding is minimal, so this procedure will extract virtually every source in the region. A sample ratioed pair of frames is illustrated in Figure 1; it shows the source WL 20 (Wilking and Lada 1983), which we discovered to be a nearly equal magnitude binary. The results of the remainder of the survey can be described succinctly; no new sources were discovered to a conservative completeness limit of $m_K = 14.5$. All previously known sources were detected.

Calibration was by observing standard stars from Elias *et al.* (1982) and by comparison with the magnitudes measured previously for the objects detected in the frames. Both calibrations were in satisfactory agreement.

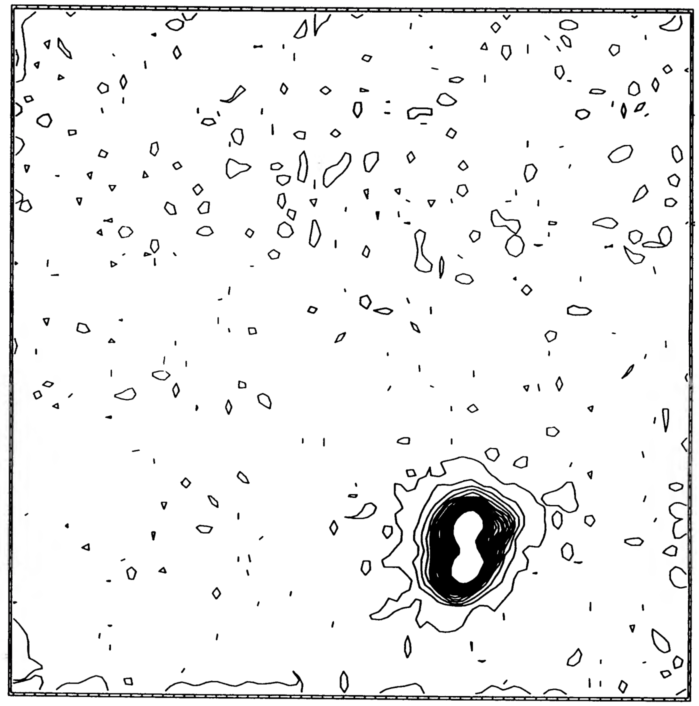

FIG. 1.—Typical camera frame. The pixel size is 0″85, and the frame is 54″ on a side. It represents the ratio of the observations centered at 16ʰ24ᵐ13ˢ1, −24°32′39″ and at the same R.A. but 51″ north. The bright double source is WL 20 (Wilking and Lada 1983). The rms noise in this frame is $m_K = 17.9$ pixel^{-1}.

III. INTERPRETATION

Figure 2 shows the distribution of K magnitudes for members of the embedded stellar cluster. The data have been taken from Wilking, Lada, and Young (1989) and references therein, and from Elias (1978). Where a source has been identi-

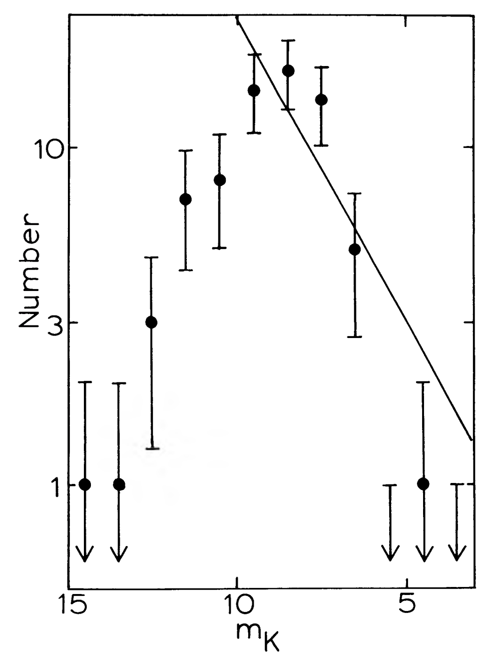

FIG. 2.—Magnitude distribution at K of known sources in the Rho Ophiuchi cluster (from the summary of Wilking, Lada, and Young 1988). The diagonal line has a slope of 0.45 (see text).

fied as a binary but without individual magnitudes, we have plotted it as two sources each at half the total flux.

Given the quoted flux limits of the surveys on which Figure 2 is based, it seems plausible that the completeness limit is roughly $m_K = 10$, near the turnover of the source counts. This interpretation has been adopted by Wilking, Lada, and Young (1988), for example. Therefore, we have fitted the source counts for $m_K < 10$ with functions of the form $n(S) = CS^{-a}$, where $n(S)$ is the number of sources per logarithmic flux interval centered on flux S and C is a constant. The smallest value of a that is compatible with the data is roughly 0.45; this fit is shown in Figure 2. Even for this value, the fit predicts significantly more bright sources than have been detected; a steeper power law would seem more plausible to avoid this overestimate.

This power law can be used to extrapolate down to the limit of our survey to test whether the apparent turnover in the number distribution is intrinsic or the result of incompleteness. The region surveyed has already been mapped to a relatively deep limit, $m_K \sim 12$ (Wilking and Lada 1983). Therefore, a power law with spectral index $a = 0.45$ was normalized to the number of sources in the surveyed region with $m_K < 12$. This extrapolation predicts that we should have found ~ 14 new sources. This prediction can be altered slightly by alternate choices of normalization or power law index; for example, a larger index than 0.45 would lead to a prediction of more sources. It is difficult to find plausible parameters that would not predict eight or more new sources. Assuming that the probabilities are Poisson-distributed, the *a priori* likelihood of our result is less than 0.0003 in the absence of an intrinsic turnover in the number counts.

The turnover in number of sources is the major result of this *Letter*. The source luminosity at which this turnover occurs can be estimated from the extensive measurements and analysis of embedded source energetics by Wilking, Lada, and Young (1989). Their analysis is based on calorimetry and, to first order, is independent of the level of extinction or assumed characteristics of the underlying source such as ultraviolet spectral energy distribution. Following their approach, we consider the conversion of K magnitude alone to source luminosity.

The maximum luminosity that would escape detection in our survey depends on the portion of the output of the source that lies in the K bandpass. A simple model for computing this quantity is a power-law spectrum between 2 and 100 μm; this has the advantage that it is similar to the approach used by Lada (1987) to divide the embedded sources into evolutionary categories. The spectral index is defined as b in

$$\nu F_\nu = C\nu^{-b} ,$$

where C is a constant, ν is the frequency, and F_ν is the flux density per frequency interval. We have made comparisons for the sources with detailed photometry in Wilking, Lada, and Young (1989) and find that simple power laws provide an estimate of the detected luminosity within roughly a factor of 2. For a distance of 160 pc and $b = 0$, $m_K = 14.5$ corresponds to a detected luminosity between 2 and 100 μm of $L \sim 0.001\ L_\odot$. This power law is close to the average for the embedded sources (Wilking, Lada, and Young 1989). It seems plausible to attribute the turnover in number counts to a dearth of embedded sources with luminosities between 0.01 and 0.001 $L_\odot$, corresponding, respectively, to $m_K = 12$ and 14.5.

For $b < 0$, the detected luminosity is of the same order as used in our estimates unless the spectrum continues without steepening to much shorter wavelengths than 2 μm, and our I band image shows that such continuation does not occur. However, for indices $b > 0$ (i.e., cold spectra), the luminosity can be substantially larger—e.g., $m_K = 14.5$ and 12 correspond respectively to 0.01 $L_\odot$ and 0.1 $L_\odot$ for $b = 0.5$. It cannot be strictly excluded that there is a large population of very low luminosity objects with very cold spectra, but such an explanation seems artificial given that there is no strong dependence of spectral shape on K magnitude down to the completeness limit of $m_K \sim 10$, nor for the entire sample of known sources. Eighty-seven percent of the embedded cluster members have $b < 1$ (Wilking, Lada, and Young 1989).

The behavior of the luminosity distribution discussed above can be interpreted in terms of the mass function in the embedded cluster. To do so, we used the stellar evolutionary models of D'Antona and Mazzitelli (1985) and interpolated to the luminosities and ages of interest. For ages of 3×10^6 yr to 10^7 yr, the masses corresponding to a luminosity of 0.01 $L_\odot$ range from 0.05 to 0.09 $M_\odot$. For 0.1 $L_\odot$, the corresponding range is 0.25 $M_\odot$ to 0.4 $M_\odot$ for the range of possible ages. Our data are therefore consistent with other evidence that the stellar mass function flattens at one-tenth to a few tenths of a solar mass (e.g., Larson 1986).

The exact luminosity where this flattening becomes apparent in the ρ Oph cluster is not yet well determined, both because of the spectral uncertainties in converting near infrared observations to luminosities and because the statistics of detected objects do not allow us to place the turnover point accurately between $m_K = 10$ and 12. This second issue can be settled by additional deep mapping of a larger area.

Until a very deep survey becomes available at longer wavelengths, e.g., from ISO or SIRTF, the first issue can be dealt with only by using illustrative examples. Suppose we assume the luminosities appropriate to a spectral index of $b = 0.5$ for the observed sources and convert to the masses appropriate to ages of 3×10^6 yr. If we assume the IMF of D'Antona and Mazzitelli (1986), $F(M) = aM^{-k}$, $k = 1.68$, we predict that there should be 2.2 times as many sources with $12 < m_K < 14.5$ ($0.05\ M_\odot < M < 0.25\ M_\odot$) as there should be with $9.5 < m_K < 12$. From the six sources observed in the latter magnitude range, we should have found 13 in the former range, whereas we found none. For this choice of parameters $k = 1$ would predict roughly equal numbers of stars in the two magnitude ranges; our data therefore suggest $k < 1$. Other choices of the spectral index b lead to qualitatively similar conclusions so long as $b < 1$; that is, so long as the lowest luminosity sources do not have much colder infrared spectra than those of the rest of the embedded cluster.

For brown dwarfs to add significantly to the mass of a stellar population requires $k \geq 2$. Within the limitations discussed above and if the area we have mapped is typical of regions where low-mass stars form, our data would suggest that the "missing mass" is not made of brown dwarfs just below the bottom of the main sequence.

IV. CONCLUSION

We have mapped an area of 20 arcmin^2 in the ρ Oph molecular cloud to a detection limit of $m_K = 15$. All sources known from previous less sensitive maps of the same region were detected, but we found no additional ones. Unless the very low mass stars have extremely cold infrared spectra, the formation of stars and substellar objects below a few tenths of a solar mass appears to be suppressed in this region. If this result is true generally in regions of low-mass star formation, large brown dwarfs are unlikely to contribute significantly to the "missing mass."

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