STAR FORMATION

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Prologue

Judging from the poster that the Organizing Committee has selected to announce the celebration of Guido Münch Jubilee, one can easily conclude that the main characteristics of the process of star formation as emerged in recent years through the combined efforts of multiwavelengths studies of molecular clouds, were already known, here in Granada, several centuries ago to the masters who built and enriched the enigmatic palace of the Alhambra. As we can appreciate from a quick inspection of the picture, it is rather obvious to infer that stars are the byproduct of a quite complex series of phenomena, each connected to, and somewhat dependent on, the others. Also, stars do not form in isolation, but rather in clusters or associations, with a strong tendency for the largest ones, also the most massive ones, to sit in the middle of the distribution. Moreover, smaller and less massive stars outnumber their massive counterparts, apparently obeying a power–law distribution. Finally, but with the benefit of doubt, it appears that the idea that the whole process reflects an intrinsic fractal nature was also put forward at the time. With this background in mind, let us now turn to the new emerging aspects of the study of star formation.

1. Introduction

Star formation is a fundamental chapter in the study of the structure and dynamics of the interstellar medium. As circumstantial observational evidence has been accumulating over the years, we are now in the position to pinpoint the essential aspects of the complex phenomena that concur in the process of the formation of new stars out of the raw interstellar material. Observations have strongly indicated that the sites of current star formation in the Galaxy occur within the densest regions, called cores or clumps, of molecular cloud complexes. On the large scale, molecular clouds are dominated by forces (rotation, magnetic field, turbulence) that counteract gravity in the tendency to initiate dynamical collapse to form stars. At the small scale of the cold cores, eventually gravity takes over, due to the slow diffusion of the restoring forces, and star formation actually ensues. Several informative accounts on both the observational and theoretical aspects have been published recently and useful references are the reviews by Shu, Adams and Lizano (1987), Mouschovias (1987), Pudritz (1988), Walmsley (1988), and Zinnecker (1988).

In this review, rather than trying to cover all the different topics, an almost impossible task anyway, I prefer to concentrate on just one particular aspect that represents an interesting example of recent developments in the field and that has not been covered in previous summaries: the study of young stellar clusters still deeply embedded in molecular clouds. In my view, this topic is extremely instructive since *a)* it offers the possibility of addressing the problem of star formation in groups and of probing *in situ* the origin and development of the luminosity function of the newborn stars; and *b)* it provides the unique opportunity to test the predictions of the theoretical models, mainly developed for individual objects in rather idealized cases, on very large and statistically significant samples. It is important to stress that the derivation of both the luminosity and initial mass functions has been hampered by the limitation of resting on samples that were either heterogeneous, as in the case of field stars, or homogeneous but relatively old, as for open clusters, or young but rather poor in objects, such as the OB associations (cf. the discussion by Dr. Larson in this volume). In most of these cases the star formation process had long been exhausted and other dynamical phenomena might have had an influence in the shape of the observed distributions.

The recent developments brought about by the advent of near-infrared (NIR) array cameras offer the unsurpassed advantage of removing, at least in principle, some of these fundamental constraints, and the first scientific results are already circulating (cf. Gatley, DePoy and Flower 1988 for a first account). Admitedly, the whole subject of the luminosity function of embedded clusters is still in its infancy and subject to rapid, and perhaps controversial developments: therefore, some, or most, of the results and conclusions presented here must be taken *cum grano salis* and should be considerd only as tentative and preliminary. As a proof, the largest part of the references quoted in this article are still in the press, or circulate as preprints. However, the excitment for this new approach to the study of star formation makes the attempt to summarize the present status worthwhile.

2. Some observations

The primary motivation for this discussion comes from the recent publication of the luminosity function of the stellar cluster in the IR core of the ρ Ophiuchi molecular complex by Wilking, Lada and Young (1989, hereafter WLY), supplemented by a *Letter* on the same topic by Rieke, Ashok and Boyle (1989, hereafter RAB). The former study represents the last of a series of systematic studies of the embedded population of this archetype of low mass star forming region, together with the Taurus–Auriga complex (Lada and Wilking 1984, Young et al. 1986, and Myers et al. 1987). Unlike Taurus–Auriga, the ρ Ophiuchi complex is characterized by a large centrally condensed core rich of young stellar objects (YSO), and by an unusually high efficiency of star formation, that has been interpreted by Wilking and Lada (1983) as suggestive of the formation of a bound cluster.

The IR core in ρ Oph has been known to harbor a high concentration of YSOs since many years (e.g. Vrba et al. 1975; Elias 1978). A different approach to the search of embedded clusters, and to the study of the frequency of their occurence within molecular clouds, has been taken by E. Lada and collaborators (1989), who have carried out an unbiased and systematic survey for dense cores traced by the high excitation CS molecule over a large region of the Orion B molecular cloud. This has led to the discovery of several individual clumps, that when deeply imaged in the NIR have revealed the presence of four rich stellar clusters within or near the massive clumps. Similar studies, but on different objects, have been performed by other groups, such as Eiroa and Casali

(1989) who have studied the IR core of the Serpens molecular cloud, and MacCaughran et al. (1989) who have attacked the Trapezium region. All of them have proved to be extremely succesful in discovering a series of very young clusters, containing hundreds of stars each, and in allowing the derivation of a luminosity function for the first time.

Before discussing in detail the properties shown by the newly derived LFs, let us summarize the necessary steps to obtain a reliable ILF, and possibly the IMF. Briefly, three steps are needed (cf. WLY for a thorough discussion):

- to derive the spectral energy distribution (SED) of each object and obtain an estimate of the bolometric luminosity;
- to classify empirically the SEDs according to some common feature, for example their shapes;
- to transform the empirical scheme into an evolutionary sequence, to possibly ascertain the physical nature of the individual objects.

While the first two steps are basically an observational exercise, very strenuous indeed, the third one relies on theoretical models that predict the emergent SED in various evolutionary phases. In fact, it is very likely to expect that the population of the embedded clusters is represented by a mixture of the youngest protostars, still in their accretion phase, and the more mature pre-main-sequence stars. These two populations have different luminosity sources and thus different SEDs. Since theoretical models of this kind have been discussed thoroughly in the literature (e.g. Adams, Lada and Shu 1988; Myers et al. 1987; Lada 1988), they need not to be repeated here.

In analogy with the derivation of the IMF for field stars in the solar neighborhood, once the LF has been determined, the MF can be obtained by the expression:

$$dN/dm = dN/dm_\lambda \times dm_\lambda/dM_{bol} \times dM_{bol}/dm, \quad (1)$$

where, as usual, the first term on the rhs represents the distribution function at a given wavelength; the second term is the analogous of the bolometric correction for stars; and the last term implies the mass–luminosity relation, that unlike the stellar case has a temporal dependence.

The knowledge of the individual SED yields the first two terms of eq. (1). Observationally, this is not an easy task since, in order to obtain the bolometric luminosity, it is necessary to cover a very large wavelength interval. In the specific case of the ρ Ophiuchi cluster, WLY have presented results in a range from 0.4 to 100μm, even though in practice the available interval is limited to $\lambda \geq 1.25\mu$m, due to extinction problems, and to $\lambda \leq 60\mu$m, due to source confusion. Considering that some sources exhibit SEDs still raising at the longest wavelengths ($\lambda = 100\mu$m), it turns out that the bolometric correction in the worst cases would amount to a factor of two (Myers et al. 1987; Strom et al. 1988; WLY 1989). Recent measurements in the sub–mm at $\lambda = 350\mu$m, beyond the peak of the emission, have quantitatively confirmed previous estimates (Ladd et al. 1989).

Based on the theoretical background developed by Adams and Shu, Lada (1987) has suggested a classification scheme of the SEDs that would correspond to a truly evolutionary scheme. In this way, the nature of each object can be tentatively assigned and the last term of eq. (1), i.e. the mass–luminosity relation, can also be evaluated. Clearly, most of the uncertainties in the derivation of the IMF reside here. While the situation is not so bad for PMS stars, since $L_{bol} = L_{bol}(M_\star)$ and can de derived by existing evolutionary tracks if the age of the cluster is known; the case for protostars is considerably more intricate. In fact, for protostars the luminosity depends upon an additional parameter, the mass accretion rate, that in turn is related to the global properties of the ambient cloud (temperature, rotation, turbulence), which are difficult to know *a priori*.

3. The LF of embedded clusters

Luminosity functions of embedded clusters have been presented by various authors. For example, Straw et al. (1989) have made a comprehensive study of the stellar mass distribution in several centers of star formation activity associated with the molecular cloud complex NGC6334. Despite the rather high sensitivity of the survey (limited to K–mag=13.5) and the possibility of detecting faint sources, the resulting mass distribution is completely sampled only for stars with mass $\geq 4M_{\odot}$. Thus, all the conclusions are restricted only to the intermediate and high mass portion of the LF.

Most of the challenge presented by the study of embedded clusters, however, comes from the study of regions in which the low mass population can be fully sampled down to masses where the LF could start showing some interesting and unexpected features. The LF for 74 members of the ρ Oph cluster derived by WLY is shown in Figure 1. Within each luminosity interval the objects are grouped according to their SED class. Also included in the histogram are sources for which only an u.l. to the total luminosity could be derived. The solid line labelled ILF denotes the initial luminosity function corresponding to the IMF computed assuming that the embedded objects have a mass-luminosity relation appropriate to H–burning main sequence stars, an assumption hard to justify. According to the authors, the most conspicuous result is the evidence of a luminosity segregation of the objects: namely, class I objects, that in the evolutionary sequence would represent the protostar population, appear to dominate the intermediate range of luminosities ($L \geq 6L_{\odot}$); while class II objects, corresponding to PMS stars, are more numerous at low luminosities. Two other properties of the LF appear to be: a *paucity* of stars of intermediate luminosity when compared with the field stars LF, and after taking into account incomplete sampling and luminosity evolution; and a *dearth* of objects of low luminosity. The two fundamental questions raised by these results are then:

1) *Is the turnover of the LF a real feature, as in the case of field stars, or is it simply due to incompleteness?*

2) *Is the deficiency of intermediate luminosity objects something to be expected on the basis of the knowledge of PMS evolution?*

In the following, I will examine in detail these two aspects, that all future discussions on the LF of embedded clusters will have to deal with.

3a. The low luminosity tail

This is the region of the spectrum where the contribution of deep imaging at NIR wavelengths using array cameras is vital. Some authors have presented LFs that indeed indicate a turnover at some faint magnitudes. As an example, MacCaughran et al.

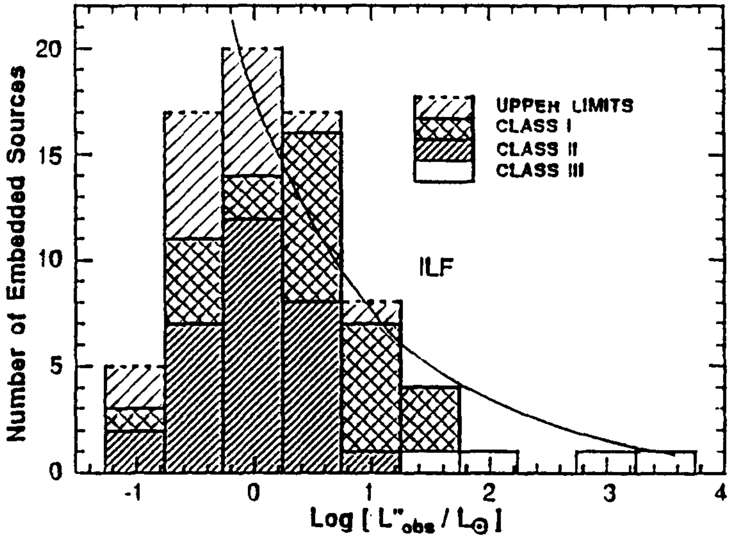

Figure 1. The luminosity function for 74 members of the ρ Ophiuchi IR core (from Wilking et al. 1989).

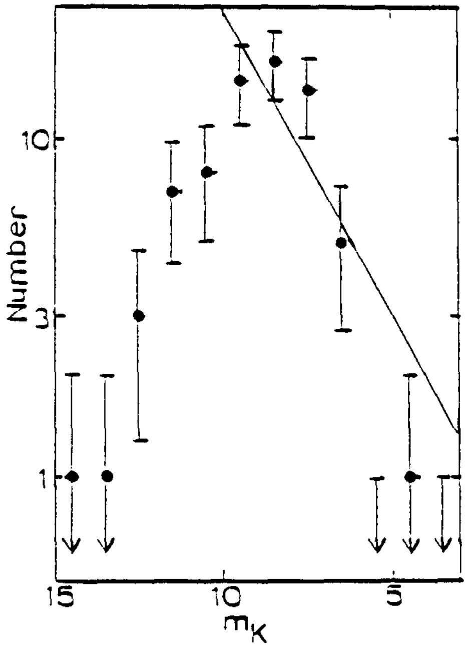

Figure 2. Distribution of K magnitudes. The straight line represents a power law fit to the source counts for $m_K < 10$ (from Rieke et al. 1989).

(1989) have surveyed the central 5'x5' of the Trapezium cluster with an almost complete sampling of the ≈ 500 members. They find a sharp cut–off at a magnitude $K \sim 13.0$, two magnitudes above the detection limit of the survey ($m_K \sim 15.5$). A similar result has been obtained by E. Lada (1989) in the case of the embedded cluster in NGC 2024.

Returning to the case raised by the ρ Oph cloud, RAB have carried out a survey of one of the regions mapped by WLY using a 68x68 pixel NIR camera. The resulting distribution function is shown in Figure 2. Despite the fact that the survey's detection limit at $m_K = 15$ is three times deeper than that of WLY , no new sources were discovered, while all the sources previously identified were indeed detected. The turnover at $m_K \sim 10$ is clearly evident, and RAB estimate that an extrapolation to magnitudes fainter than $m_K \sim 12$ would have predicted between 8 and 14 new sources , against the 2 or 3 actually detected. Of course, if this result is confirmed by further deep imaging covering a more extended region, it would represent the first independent evidence of an *intrinsic* turnover in the shape of the LF. Recently, Barsony and Burton (private communication; see also the discussion at the end of the article) claim the discovery of a large number of sources in the same field explored by WLY, but the observations apparently suffered of some problems and cannot be considered definitive as yet.

By combining the results at 2.2μm with those of WLY at longer wavelengths to derive the bolometric luminosity, RAB find that the turnover occurs at a luminosity between 0.1 and $0.01 L_\odot$, and that, therefore, the dearth in the LF refers to stars with $L \sim 10^{-2} - 10^{-3} L_\odot$, corresponding to $m_k \sim 12.5$ and $m_K \sim 14.5$ at the distance of the cloud (160 pc). The uncertainty in the exact value of the peak luminosity stems from the small statistics of the low luminosity objects, but further observations will eventually help to remove it.

At present, little can be said of the mass corresponding to the luminosity at turnover, mainly due to the uncertainties on the nature of the objects. Under the most conservative assumption that all the stars are in the PMS phase, knowing the age of the cluster (between $3 \cdot 10^6$ and 10^7 yr) and using stellar evolutionary tracks leads to an estimate of the mass in the interval $0.2 - 0.4 M_\odot$. This could be considered consistent with recent determinations of the IMF in the solar neighborhood. In this respect, it is noteworthy mentioning the great improvements in the definition of the low mass end of the IMF obtained by Leggett and Hawkins (1988) with the IR observations of M dawrfs towards the South Galactic Pole and the Hyades cluster. Their results are collected in Figure 3 and show the characteristic peak at luminosities corresponding to stars of $0.2 - 0.3 M_\odot$, and the subsequent decline down to $m \sim 0.1 M_\odot$. The reality of the rise at even fainter magnitudes, with its implications for the existence of a population of brown dwarfs, is still under debate (cf. Stobie et al. 1989, and Kroup and Tout 1989 for a different explanation of the origin of the knee in the LF); however, the turnover and the flattening appear to be an intrinsic feature of the ILF and IMF.

The indication of a similar behavior even in the case of extremely young clusters would tend to imply the existence of a preferred mass scale in the star formation process, i.e. that of the peak of the distribution. In his review, Dr. Larson argues that this scale is imprinted by the fragmentation of the large scale molecular clouds into clumps or cores of sub–stellar mass. This viewpoint differs from that advocated by Shu and collaborators (e.g. Shu, Lizano and Adams 1987) for which the mass scale is determined by processes related to the evolution of the protostar itself.

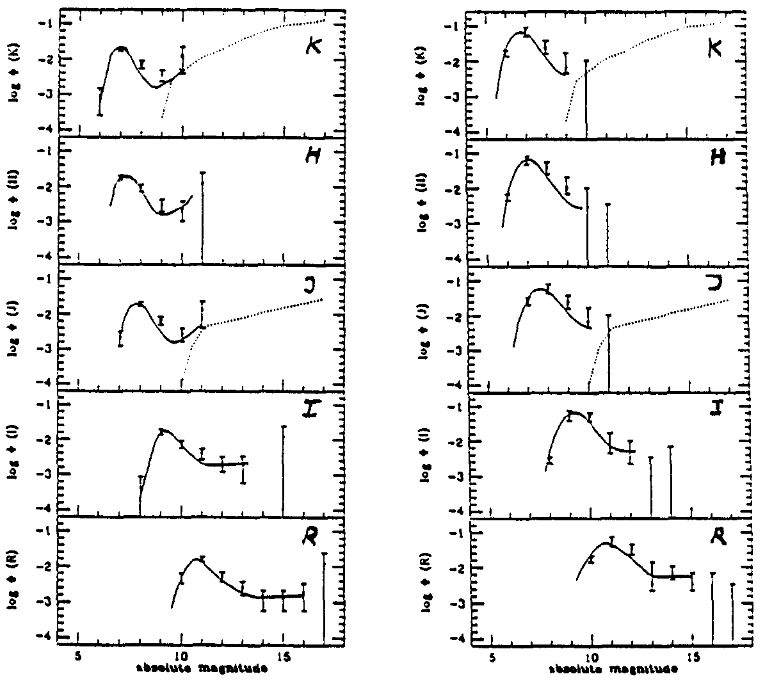

Figure 3. The Log of the luminosity function at different wavelengths for the South Galactic Pole (*left panel*) and the Hyades cluster (*right panel*) (from Leggett and Hawkins 1988).

3b. The intermediate luminosity tail

The possibility that the observed LF could show a paucity of stars of intermediate luminosity is intriguing, especially since some recent developments in the theory of protostellar and pre–main-sequence evolution of stars of mass larger than solar predict that such an effect could indeed arise (Stahler 1989; Palla and Stahler 1989). Although the observational evidence is still scant, it is worthwhile to look more in detail at the theoretical background of these results.

The basic point is that PMS stars of mass between $2M_\odot$ and $5M_\odot$, starting their contracting phase from the proper initial conditions inherited at the end of the accretion phase, are subject to a rapid *luminosity evolution* from a low to a high state. The luminosity increase takes place in a very short time compared to the typical Kelvin–Helmoltz evolutionary time, while its magnitude depends on the star mass. According to rough estimates, a $5M_\odot$ PMS star increases its surface luminosity by up to a factor of 30, going from $L \sim 15L_\odot$ at the beginning of the evolution to $L \sim 500L_\odot$ at the epoch of the flare. The most important consequence of this effect is that PMS stars of intermediate mass would first appear in the HR diagram well below the position predicted by the classical evolutionary tracks in the Hayashi phase, and only after the luminosity eruption has occured they would join the proper portion of the radiative track. This is schematically illustrated in Figure 4.

To understand how this behavior is possible one has to reconsider some basic properties of the standard theory of PMS evolution (e.g. Hayashi, Hoshi and Sugimoto 1962;

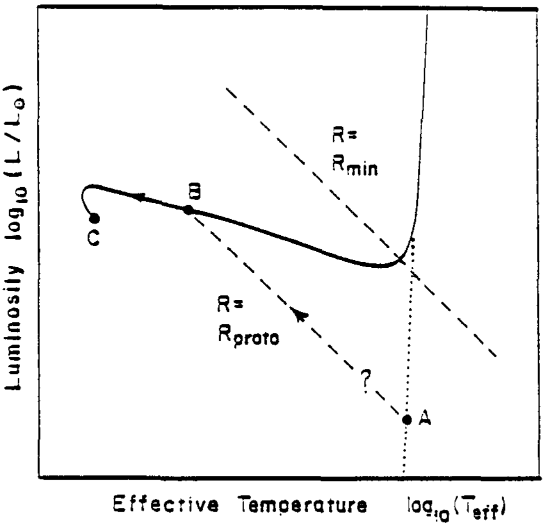

Fig 4. Schematic evolution in the HR diagram of a PMS star of $M \geq 2M_{\odot}$. R_{min} refers to the minimum radius at the bottom of the classic Hayashi track. R_{proto} is the initial radius of the star, acquired at the end of the protostellar phase (from Stahler 1989).

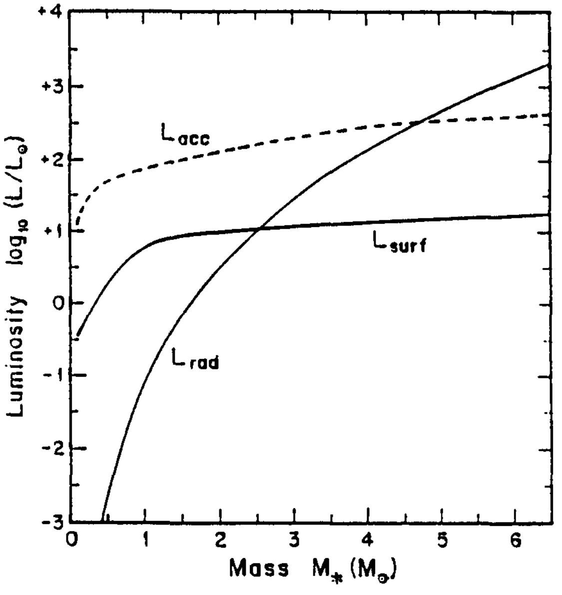

Figure 5. Luminosities of PMS stars at the beginning of their evolution, as a function of mass. L_{acc} refers to the accretion luminosity and is shown for comparison (from Stahler 1989).

Cameron 1962). According to the classical picture, PMS begin their evolution as fully convective objects due to the large initial radii, given by: $R_0 = 50R_\odot(M_\star/M_\odot)$. This relation implies that a star has a surface luminosity, L_{surf}, that greatly exceeds the luminosity that can be carried internally by radiation, L_{rad}, so that it will immediately turn convectively unstable. Stahler (1989) points out, however, that according to the results of the numerical studies of protostellar accretion (Larson 1972; Winkler and Newman 1980; Stahler, Shu and Taam 1980), radii as large as those predicted by the above relation are never reached: they typically remain an order of magnitude smaller, up to protostellar cores of $1M_\odot$. Palla and Stahler (1989) have extended previous calculations to follow the accretion phase up to cores of $5M_\odot$ and found that the radius stays fixed at $\approx 5R_\odot$, a factor of 50 less than that predicted classically. Since the surface temperature of the PMS stars in this mass range is always locked to $T_{eff} \sim 4000$K, this result implies that L_{surf} will also remain constant. On the other hand, L_{rad} is a very sensitive function of the mass, with a dependence $L_{rad} \sim M_\star^{5.5}R_\star^{-0.5}$. Therefore, as the core mass grows, L_{rad} increases dramatically and eventually overtakes L_{surf}: at this point the star will become radiatively stable, and due to the small value of the radius, will have a low luminosity when it first becomes optically visible (cf. point A of Fig. 4).

The transition where $L_{rad} \approx L_{surf}$ occurs at a core mass between $2M_\odot$ and $3M_\odot$, as can be seen in Figure 5. In order to achieve the full luminosity corresponding to L_{rad}, the cores have to wait until the internal luminosity relax to the surface due to its non-homologous contraction (classical PMS stars descend the Hayashi track homologously). The time needed for the thermal wave to reach the surface (i.e. to go from point A to point B of Fig. 4) is about the same as that needed to reach the zero–age main sequence, thus implying that there is an equal probability of finding PMS stars in the high as in the low luminosity state. Stahler (1989) discusses the possible consequences of this behavior on the mass and age estimates of young clusters, and also the predicted deficiency of sources with luminosities between 10 and $10^3L_\odot$.

4. Conclusions and future directions

The main conclusion to be drawn from the present discussion is that the study of embedded young stellar clusters in molecular clouds, with its deep implications for the understanding of the origin and development of the IMF, has now become an integral part of the research in the field of star formation. The use of IR array cameras to map extended regions of high obscuration with high sensitivity has been instrumental in overcoming the major obstacle for the development of the field, and the advent of arrays sensitive to longer wavelengths in the near future will help in removing the uncertainties on some of the issues discussed here. On the theoretical side, these observations act as a valid test to the wealth of ideas mainly developed for different contexts, and provide an effective stimulus to better refine the numerical models on which much of the interpretation rests.

The tone of this presentation has been left intentionally optimistic, perhaps even slightly overoptimistic, and little mention has been paid to the uncertainties associated with the various steps that lead to the derivation of the ILF and IMF. Among them, serious problems are caused by the difficulty of discriminating between embedded and field stars; the clustering of a large number of sources in small fields; the fact that intracluster and foreground reddening can be very non uniform; the separation between local and global extinction, and so forth. Also, it is necessary to remove uncertainties in the estimate of the bolometric luminosities by means of very deep surveys in the far-infrared (ISO, SIRTF). In order to improve source identification and remove confusion, high resolution observations in the FIR are also required. Of utmost importance is to find reliable indicators to discriminate between *protostars* and *pre-main-sequence stars*: so far, only the SEDs have been used at this purpose, but perhaps even spectral features (at 3.1 and 9.7μm) can be used as proper and unambiguous diagnostics. Finally, the comparison between the expected flux profiles from theoretical models and the spatial emission maps obtained in the submm/mm region will prove extremely useful (Adams 1989).

Epilogue

As astronomers, we have fully appreciated the impressive images obtained with the IR cameras and presented at this Conference, that have provided us with new eyes to penetrate into the inaccessible regions where the formation of new stars takes place. As participants to the meeting to honor Guido Münch, now we can better understand the deep significance of the old local saying:

"*...no hay en la vida nada como la pena de ser ciego en Granada*".

Acknowledgements

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Discussion:

TERLEVICH, E.: It is very dangerous to base your IMF on luminosity functions of cluster cores. It has been predicted long ago (analitically) and more recently confirmed (numerically) that the dynamical evolution of star clusters tends to deplete the core of light stars and populate the halo with them, in time scales comparable to a few (1-2) crossing times. In order to get a representative IMF therefore, you have to sample your cluster stars to regions, at least 4 or 5 core radii. In other words, you must be concerned about completeness, not only in deeth but also on width. It is very difficult to observe the haloes of open star clusters, but, as they say in the North of England: "where there is muck, there is brass".

PALLA: Although in principle your remark is correct, I think it is still premature to apply it to the ρ Oph IR cluster for which the suggestion of a forming bound cluster is only tentative. Your results clearly apply to systems where both the total number of stars and the radius are known.

BARSONY: The Rieke's result that there is a turnover at low luminosities in the initial luminosity function based on their 2μm data is wrong. We (M.Burton, A.Russell, J.Carlstrom) have unpublished data obtained with the KPNO 2μm camera which show at least 20 new sources in the same field (10'$\times$10') as the previously published survey of Wilking and Lada. This unpublished result is entirely consistent with the expected, accepted IMF.

PALLA: Rieke's survey is admidtedly limited to a smaller region than that sampled by Wilking et al. It is clear that theirs is the first attempt to fully image the ρ Oph IR cluster: future observations, like yours, will certainly help clayifying the important issue of a possible turnover at low luminosities.