LUMINOSITY DISTRIBUTION OF YOUNG STARS*

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ABSTRACT

ISO has provided an update to the luminosity functions of young stars in close by star forming regions. There is typically a factor of two increase in the numbers of known members. This is mainly achieved in the low luminosity end of the distribution. With the new samples the form of the initial mass function has been deduced to increase till brown dwarf mass domain. The features of luminosity function have been successfully fitted with models containing deuterium burning in the pre-main sequence stars. These first results demonstrate that ISO has lived up to its potential in allowing major advances being made in our understanding of the formation of stellar clusters in the solar neighbourhood.

Key words: luminosity function; star formation; pre-main sequence evolution.

1. INTRODUCTION

Luminosity function is a statistical approach to study properties of a sample of stars. The importance of a luminosity function is not obvious. In itself it does not directly reveal any fundamental physical parameters of interest of the sample studied. The reason why luminosity functions are interesting is due the fact that they can be addressed both observationally and theoretically. Luminosity function is the "meeting place" of observers and theoreticians. Major advances in our understanding of the star formation process have been made by studying individual objects in great detail. Equally important is to understand the bulk properties of newly born stars. Luminosity function is the way to study star formation on the scale of a star forming region. Without understanding the luminosity function of young stars our picture of star formation is not complete. This is not a straightforward task. Extracting the (initial) mass function of main sequence stars from the luminosity function is already complex. With constantly evolving young stars the interpretation of the luminosity function gets even more complicated. On the other hand, in the complexity is also the potential: luminosity function of young stars contains the information of initial mass function, star forming history and evolution of newly born stars in it. By understanding the luminosity function we are a long way ahead in understanding the process of star formation.

In order to construct the observed luminosity function of young stars it is essential to obtain infrared observations. There are two reasons for this: (1) due to circumstellar matter a significant (sometimes dominant) fraction of the bolometric luminosity is emitted in the infrared; and (2) due to extinction optical observations provide inventory only of objects at the front side of a star forming cloud. Prior to ISO, the constructed samples had to rely on IRAS and ground based near infrared data. While the longer IRAS wavelengths provide a view practically free of cloud extinction, the sensitivity is not sufficient to address the questions related to very low mass stars. Modern ground based near infrared imaging provides the sensitivity down to the detection level of young brown dwarfs, but in the near infrared the extinction is still not negligible making interpretation very complicated. With the ISO data it is possible to achieve the sensitivity needed for brown dwarfs at wavelengths in which extinction is low enough to require less complex corrections.

2. PRE-ISO WORK

After the question of luminosity functions of embedded stars was first addressed by Wilking & Lada (1983), the attention was soon focused on the exploitation of the IRAS data. IRAS provided several advantages over other possibilities available during the 80s. IRAS had covered practically the whole sky and therefore a full census of the close by star forming regions could be done. The wavelength coverage extending past mid-infrared into areas without significant extinction was another advantage of IRAS. There were also drawbacks. The IRAS resolution was not sufficient to disentangle the sources in the most crowded areas of the close by star forming regions. Also the sensitivity was not sufficient to address the questions of very low mass stars and brown dwarfs.

When IRAS data was combined with ground based optical and near-infrared measurements, it was possible, with certain assumptions, to deduce the bolometric luminosity of a young star. An important note

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with the concept of bolometric luminosity is that it is not only meant to include the bolometric luminosity of the star, but also any possible contribution from accretion luminosity radiated by the disk. By deducing the bolometric luminosity of each known member of a star forming region, it is possible to construct the bolometric luminosity function. This was done for ρ Oph (Wilking et al. 1989), Taurus-Auriga (Kenyon et al. 1990) and Chamaeleon I (Prusti et al. 1992). By comparing these bolometric luminosity functions to the theoretical luminosity functions by Stahler & Fletcher (1991), Prusti et al. (1991) concluded that we have not been able to see the main accretion phase luminosity in the studied samples. This may be caused by two reasons. (1) The standard theory of star formation (Shu et al. 1987) is not applicable to the close by star forming regions. (2) The IRAS based samples did not include the true protostars at their main accretion phase.

In the 90s the attention turned more and more toward near-infrared work. With the availability of large near-infrared arrays it became possible to observe close by star forming regions below the sensitivity limits required for young brown dwarfs. The latest example of such a survey is that of ρ Oph by Barsony et al. (1997) who list 4495 targets in a one square degree area. This number can be compared with that of about 100 used for bolometric luminosity functions although one must remember that the 4495 stars are both cloud members and field stars. The fact that one cannot easily state how many of the targets in ρ Oph are cloud members hints that there is a problem in using this sample for luminosity function. The basic problem is that there is a fair fraction of young stars with infrared excess which cannot be distinguished from reddened background stars with near-infrared data alone. The same thing can be illustrated with an example. If we know a brown dwarf with an age of a few millions years in a close by molecular cloud, it will be no problem at all to detect it with modern near-infrared arrays. The problem is that if we observe a faint, red near-infrared target projected on a star forming region, there is no way to tell from the near-infrared colours if it is a brown dwarf with some infrared excess or extinguished background giant behind the cloud.

To avoid problems related to the handling of extinction one has to study somewhat older regions which have already cleared significant amounts of the original dust contents. IC 348 seems to be suitable star forming region for such studies as Lada et al. (1998) could conclude that the peak of the mass function is around $0.2 - 0.3\,M_{\odot}$. In general the problem of older regions is that the very low mass stars have already evolved significantly and dropped in luminosity so much that they become hard to detect. With old regions the extinction problem diminishes, but at the same time the low mass stars start to be beyond reach due to pre-main sequence evolution into lower luminosities.

Against this background the ISO potential is obvious: observations at mid-infrared wavelengths with significantly less problems with extinction while preserving the sensitivity to probe objects with masses below the brown dwarf limit.

3. YOUNG STARS

In this section the observational and theoretical aspects of star formation from the ISO and the luminosity function points of view are reviewed.

3.1. Observational Aspects

Since the connection of infrared spectral index to pre-main sequence evolution was established by Adams et al. (1987), the observers have classified young stars into three classes. Class I contains targets with rising mid-infrared spectral energy distribution. Class II objects have declining mid-infrared spectrum, but still with infrared excess on top of the stellar emission. Class III stars show only a very modest infrared excess or no excess at all so that their pre-main sequence nature has to be verified by other means (e.g. X-ray activity). Later, based on sub-mm observations Class 0 was added to the categories (André et al. 1993). Class 0 objects differ from Class I by being undetectable in the mid-infrared and by having a modified single temperature blackbody spectral energy distribution which is narrower than that of a Class I object.

By using various observational arguments (relative number counts, kinematic outflow ages etc.) it has been possible to estimate the time scales a young star spends in various stages. Class 0 phase is estimated to last of the order of 10^4, Class I 10^5 and Class II a few times 10^6 years while Class III stage is reached within 10^7 years. When taking the time scales into account one can conclude that by catching the Class II and III objects one is practically complete for luminosity function unless the sample is dominated by objects younger than 10^7 years. On time scale arguments one can also conclude that Class 0 objects are irrelevant for luminosity functions as the solar neighbourhood does not seem to contain any star forming region which has started to produce stars earlier than 10^5 years ago.

For ISO Class 0 was a challenge as most of the luminosity is emitted in the sub-mm wavelengths. However, as mentioned above, in practice Class 0 sources do not contribute significantly to the luminosity function of young stars in close by regions. Also Class III sources are problematic. One cannot distinguish young stars without infrared excess with ISO broad band photometry alone and the ISO observing programme did not contain any suitable spectroscopy surveys which would provide distinction between Class III members and fields stars in large enough numbers. Therefore observationally ISO can best address the question related to luminosity functions of Class I and II objects.

3.2. Theoretical Aspects

The early stellar evolution can be divided into two phases. The first protostellar phase is the period when most of the mass is accreted (Shu et al. 1987). During the second phase the young star is contracting toward the main sequence along pre-main sequence tracks (D'Antona & Mazzitelli 1997). With the concept of the birthline (Stahler 1983) it was possible to combine these two evolutionary stages into a single picture of star formation.

In the standard picture of star formation (Shu et al. 1987) a protostar reaches at a very early stage a central temperature of 10^6 K and deuterium is ignited. After deuterium burning is started the continuing accretion brings new deuterium into the star and convection brings it into the stellar interior. The protostar evolves this way along the birthline with mass increasing. With intermediate mass stars the evolution is more complicated as the deuterium burning moves into a shell at a later stage, but the concept of the birthline remains till the point where the birthline crosses in the HR-diagram the main sequence (Palla & Stahler 1990). This crossing point indicates the evolutionary stage where the normal main sequence nuclear processes start independently of possible further accretion of matter on the star. The mechanism which stops the accretion is not known, but when this happens the protostar stops evolving along the birthline and, in the case of a low-mass star, evolves along the pre-main sequence tracks instead.

We can map some observational young star categories into the theoretical picture. Class III stars are often associated with the so called naked T Tauri stars which demonstrate pre-main sequence signatures, but do not possess infrared excess. These stars are generally closer to the main sequence than to the birthline and can be considered "old" young stars. Class II stars are usually associated with classical T Tauri stars. In the HR-diagram they are closer to the birthline than Class III stars although the border between Class II and III is not that clear with some Class III stars being younger than some Class II stars. With Class I the mapping to the theoretical scenario becomes more difficult. The Class I stars do not generally seem to possess the luminosity expected for protostars. Therefore it is likely that Class I stars have already passed the main accretion phase and they have already left the birthline. The best candidates for true protostars can be found from the Class 0 group. However, even they have the luminosity problem stated above for Class I. At this stage it is unclear if Class 0 stars are simply yet another category even closer to the birthline or that they are protostars and our knowledge of the accretion process is simply incomplete.

4. LUMINOSITY FUNCTION

A luminosity function of a sample of stars depends on three factors: (1) the initial mass function i.e. the relative probability for the creation of stars of different masses at a particular time and location; (2) the star formation rate i.e. the time dependent efficiency of converting interstellar matter into stars at a given location; and (3) the stellar evolution i.e. the luminosity of stars of different masses as a function of time. It is not possible to separate these factors from the observed luminosity function, but one can test the compatibility of a set of hypotheses by making a model luminosity function based on assumptions and by comparing it to the observed one. Clearly, the selected sample of stars limits the choice of realistic assumptions. With a sample of Population I field stars in the solar neighbourhood different astronomical questions can be addressed than with a sample of young stars in a close by molecular cloud.

In the following three sections the main factors of luminosity function are discussed in view of constructing it for a sample of young stars.

4.1. Initial Mass Function

After the classical work on luminosity functions by Salpeter (1955), much of the work done has been aimed to deduce the initial mass function (IMF). Especially with Population I stars, one can state that both the star forming history in the solar neighbourhood and the luminosity evolution, by selecting main sequence stars only and taking into account their main sequence life times, are much better known factors in luminosity function than the IMF. This way one can conclude that for main sequence stars IMF is the unknown to be extracted from the luminosity function.

The goal of obtaining the IMF was originally the primary motivation to study luminosity functions of young stars. The idea behind being the possibility to find the IMF by looking directly the initial state of a stellar cluster. However, for young stars not only the IMF is poorly known, but also stellar evolution and star forming history are more or less equally badly understood factors.

In the most recent review of the IMF Scalo (1998) proposes to use three different power laws in three different mass intervals. Scalo (1998) notes that there is no indication that IMF has a power law nature and the suggested power laws are simply computationally convenient for those needing IMF as an input parameter for modeling. Furthermore, there seems to be growing evidence of varying IMF. Given the uncertainty in the universality of the IMF, the most reasonable approach with young stars is to follow the proposal by Scalo (1998) to use the power laws with the suggested "error bars" indicative of the possible IMF variation. For the very low mass stars one has to assume either a rising, flat or declining power law. Then the only question of IMF one can address with young stars is the compatibility of the assumed IMF with the observations.

4.2. Star Formation Rate

Star formation efficiency is an often quoted quantity in observational and theoretical studies of the star formation process. It is usually deduced by dividing the mass in stars by the sum of the stellar and interstellar matter masses. For luminosity function this integrated property is not enough, but the instantaneous star formation efficiency during the whole star formation episode is needed. This time dependent star formation rate gives for every moment the "speed" interstellar matter is converted into stars.

There is another factor to be considered together with the star formation rate. The moment we happen to witness of the full star formation episode of a region has a large influence on the luminosity function (Fletcher & Stahler 1994b). This means that two clouds, which have the same IMF and the same time dependent form in the star formation rate but different start time for star formation, show different luminosity functions. Formally this star forming history can be included in the concept of star formation rate.

The interest in disentangling the star formation rate from a luminosity function is that one may see whether star formation occurs in burst(s) of short duration or in a more continuous manner. A burst of star formation results in a sample of coeval stars, which may demonstrate a feature in the luminosity function due to the common evolutionary stage (see below) of the dominating population of stars. A more continuous star formation generally yields smooth luminosity functions.

4.3. Stellar Evolution

The qualitative picture of early stellar evolution was formalized in the context of luminosity functions by Fletcher & Stahler (1994a) who then continued constructing theoretical models for young stellar clusters (Fletcher & Stahler 1994b). There is one point to mention of these theoretical luminosity functions with respect to stellar evolution. The protostars show up as a prominent peak in the luminosity function which is especially clear at the earliest stages of cluster formation. The protostar luminosity peak is a consequence of the calculated accretion rate and the mass-radius relation of accreting stars: in conditions present in the ρ Oph cloud most protostars should radiate $50\,L_\odot$.

Also the pre-main sequence stellar evolution contains phases causing features in the luminosity function. Zinnecker et al. (1993) noted the significance of deuterium burning for the luminosity function. Effectively deuterium burning at the pre-main sequence phase halts the continuous decrease of the bolometric luminosity till the deuterium has been exhausted. This gives a feature in the luminosity function corresponding the deuterium burning phase of stars with masses around the peak of the observed IMF.

There seems to be a discrepancy between the concept of the birthline and a feature in luminosity function due to deuterium burning in the pre-main sequence phase because the birthline is based on the assumption of deuterium burning at the protostar phase. This potential discrepancy provides an interesting probe to early stellar evolution. If we consider a star just above the brown dwarf mass limit, then we can rather safely state that the collapse time scale is too short to allow high enough temperature in the centre to ignite deuterium. For these objects the deuterium burning occurs during the pre-main sequence evolution after significant contraction of the core. On the other hand, if we consider a star two times more massive than the Sun, then the accretion time is probably long enough to allow deuterium ignition and appearance of the star on the birthline. In this case the deuterium burning occurs during the accretion phase and is practically invisible due to the high accretion luminosity which will dominate the observed fluxes. The interest is in the mass region around few tenths of a solar mass. In that mass interval the ignition of deuterium depends on the accretion rate: the quicker the accretion the higher mass star has deuterium still left at the beginning of the pre-main sequence phase. Therefore a deuterium burning feature in the luminosity function can be used to address the questions of protostellar time scales and accretion rates: both of fundamental importance in our understanding of the star formation process.

5. ISO RESULTS

The latest ISO results will be reviewed: expansion of the population of known young stars in close by clouds; pushing the completion limit of the luminosity function into the regime of very low mass stars and brown dwarfs; and constraining the evolutionary time scales based on statistical properties of the young star samples.

5.1. Young Stellar Objects in Close by Star Forming Regions

In order to draw any meaningful conclusions of luminosity functions one has to know the level of completeness in the used samples. The ISO observations of close by clouds have typically increased the number of known members by a factor of two (Nordh et al. 1996; Bontemps et al. 1999; Kaas et al. 1999). This increase is mainly due to low luminosity objects as ISO has been able to move the completeness limit to the brown dwarf domain.

There are many reasons for the increase of the samples. Firstly, the areas covered have increased. Secondly, extinction in the near-infrared is still significant enough to hide some stars which become only visible at the longer ISO wavelengths. The third reason is astronomically the most interesting one. As mentioned earlier, some young stars with infrared excess cannot be distinguished from reddened background stars in the near-infrared because the reddening and the infrared excess change the colours in a similar way. With the ISO colour [14.3/6.7] an infrared excess can easily be distinguished from stellar photosphere. The advantage comes from the fact that extinction at 6.7 and $14.3\,\mu$m is very similar (see e.g. the tabulation by Mathis 1990). By having the filters at both sides of the $9.7\,\mu$m silicate absorption feature ISO provides a colour which has a very weak dependence on extinction.

The fact that the ISO colour [14.3/6.7] is not that sensitive to extinction allows to draw directly conclusions from the distribution of the colour values. Chamaeleon I sample indicates that either stars have a clear infrared excess or no excess at all. There are hardly any intermediate cases (Nordh et al. 1996). This confirms an earlier result by Skrutskie et al. (1990) who concluded, based on ground-based near-infrared and $10\,\mu$m data, that there is a lack of intermediate infrared excess cases. This indicates a very short time scale for the disk removal process around pre-main sequence stars. The more recent study of Serpens (Kaas et al. 1999) confirms the division of young stars to clear excess and non-excess categories.

By selecting samples based on infrared excess in the ISO wavelengths one is going to miss the pre-main sequence stars which have already lost their circumstellar dust shell and disk. We know from X-ray and Hα surveys that there are young stars in close by clouds which do not possess infrared excess. There are very young stars without infrared excess, but one can state that generally the stars younger than a few times 10^6 years have infrared excess and older stars have lost it. Although selection by infrared excess clearly does not provide complete census, it may be that the ISO samples are better defined than samples based on e.g. X-ray and Hα data because of the above mentioned quick transition from a star possessing infrared excess to a star without.

5.2. Low Mass End of the Initial Mass Function

Most of the newly discovered members in close by regions are of low luminosity and consequently of low mass. This allows addressing the question of the very low mass end of the IMF. Olofsson et al. (1999) show that in Chamaeleon I the IMF in the mass range $0.1 - 1\,M_{\odot}$ continues to rise slowly toward lower masses. There is a very good match with the proposed IMF slope by Scalo (1998). If this slope remains the same (or becomes more shallow or turns down) in the brown dwarf mass range, then it is possible to conclude that of the total stellar mass only a tiny fraction is in brown dwarfs.

The Chamaeleon I mass function seems to reach a peak at about $0.1\,M_{\odot}$ (Olofsson et al. 1999). However, it is not clear what is the completeness level of the mass function bins in the brown dwarf domain. Consequently, at this stage one can not claim that there is evidence of the mass function truly turning down after $0.1\,M_{\odot}$. On the other hand, the recently discovered brown dwarf in Chamaeleon I (Neuhäuser & Comerón 1998) is easily detected by ISO. This gives confidence to the potential of the ISO data in resolving the shape of the IMF in the brown dwarf mass range. When the uncertainties involved in the lowest flux levels have been quantified, then the question of IMF in the brown dwarf domain can be addressed.

5.3. Stellar Evolution and Features in the Luminosty Function

The $14.3\,\mu$m flux distributions and the luminosity functions of Chamaeleon I, Serpens and ρ Oph all show features (Nordh et al. 1996; Bontemps et al. 1999; Kaas et al. 1999). In principle these features could be caused by features in the IMF or by peculiarities in the star formation history within the cloud in question. However, the most plausible explanation can be found from the stellar evolution because models containing deuterium burning predict such features (Zinnecker et al. 1993; Censori & D'Antona 1998).

As mentioned earlier, features are always clearer if the sample is coeval. However, the age dispersions among T Tauri stars in various star forming regions suggest that star formation process can be maintained at least several millions of years. Therefore it is most encouraging that Bontemps et al. (1999) can find a reasonable fit to the features of the luminosity function of ρ Oph with star formation spanning two million years. The fact that the features can be associated with deuterium burning in pre-main sequence stars indicates that luminosity functions can indeed be used to constrain models of early stellar evolution.

6. CONCLUSIONS

The first results of luminosity functions based on the ISO data are promising. The extinction handicap of the near-infrared data can be avoided or at least better controlled with the ISO measurements. The samples of known members in close by star forming regions have increased typically by a factor of two. This increase is especially evident at the low luminosity end giving possibilities to address the question of the initial mass function in the brown dwarf domain. An interesting aspect of the luminosity functions is that they seem to demonstrate features. The features in luminosity function may be associated with deuterium burning phase in the pre-main sequence evolution. The prospects of major advances in the near future in the interpretation of luminosity function of young stars with the ISO data are excellent.

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