FROM MOLECULAR CLOUDS TO STARS

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Abstract

In this short review we outline some aspects of the present understanding of the star formation process, discussing the different processes that matter undergoes from the diffuse clouds to the pre-Main-Sequence stars. We will discuss both the global properties of the star formation process and the evolution of protostellar objects.

1 Star formation and the evolution of matter in the Universe

The understanding of the star formation process is critical in astrophysics because it is necessary for the comprehension of the evolution of stars, galaxies and finally of the Universe. Star formation is crucial for the energetics and chemistry of the interstellar medium, that may have strong implications on the origin and evolution of life. Eventually, life requires planets for its existence and the formation of planetary systems can only be studied as a part of the star forming process.

The understanding of the star formation process will make clear the origin of the mass spectrum of stars, a crucial point of the evolution of the matter in the Universe. The cycle that matter follows, since the origin of the Universe, is schematically represented in fig. 1. Stars, once formed, are producing, through nuclear reactions, elements heavier than Hydrogen. At the end of their life, part of the stellar mass will return to the interstellar medium (right side of the figure) to form new stars, part of it will be lost and will remain blocked in the remnants (White Dwarfs, Neutron Stars, Black Holes; left part of fig. 1).

Fig. 1 shows the importance of mass in the evolution of stars, in fact stars of less than ~0.01 $M_\odot$ (Dantona & Mazzitelli 1994) will never reach the temperature necessary to start nuclear reactions, and they will undergo a continuous contraction (Brown Dwarfs). More massive stars will produce energy through nucleosynthesis, their luminosity is a function of the mass as $L \propto M^4$, therefore the star life is $\propto M^{-3}$. This has a consequence for the search of extraterrestrial life: only stars of relatively low mass (less than ~ 4 $M_\odot$) may host life in their planetary

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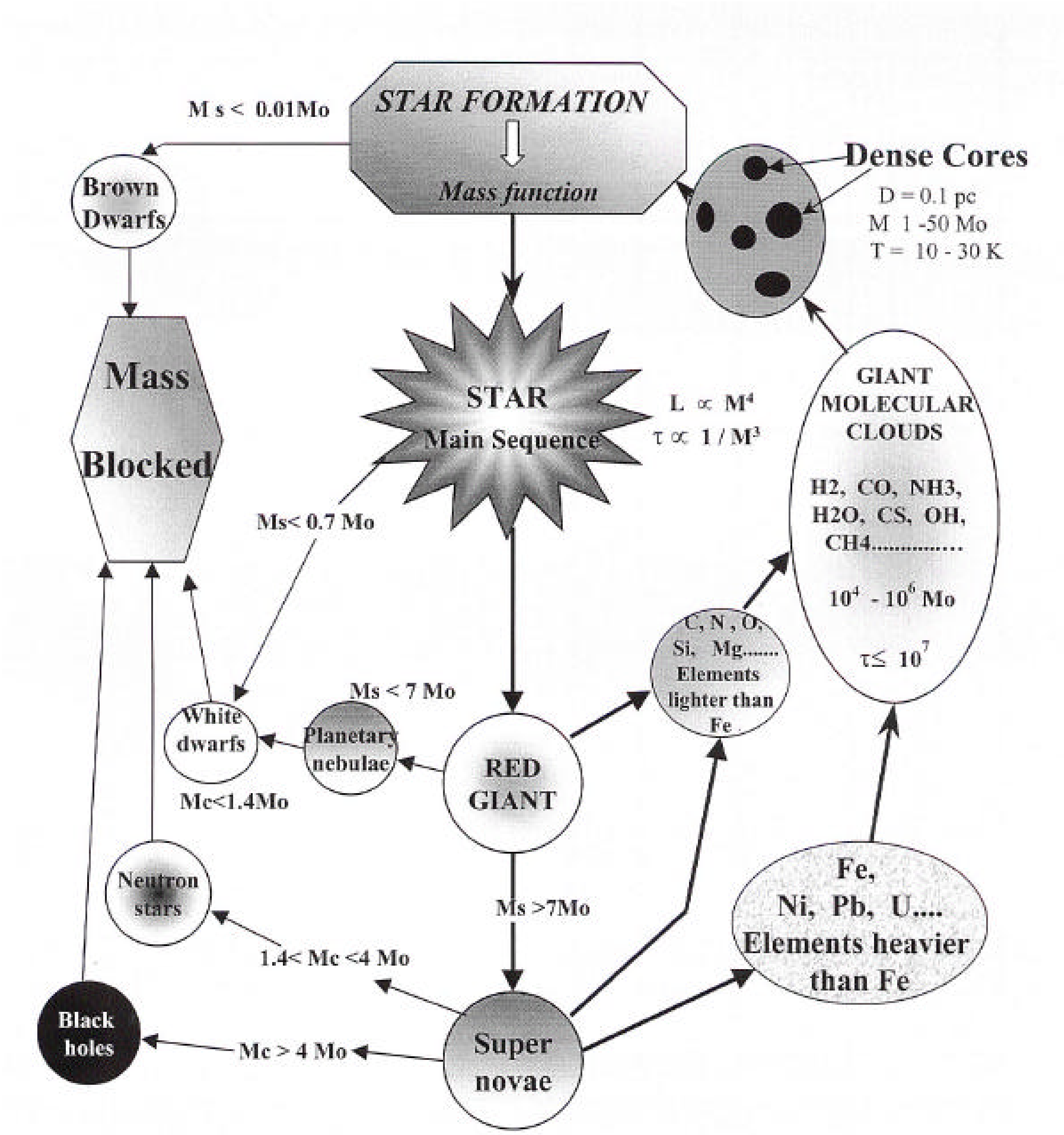


Figure 1 shows schematically, right part of the figure, the cycle that matter follows since the origin of the universe, enriching at each cycle the interstellar medium of heavier elements. Ms indicate the original mass of the star and Mc the residual mass after the mass loss

systems. Life needs a few billion years to develop and massive stars do not last so long.

The final stages of stars also depend on stellar masses: stars of less than ~7 M_o will end their life as White Dwarfs. Among them, those of more than ~0.7 $M_\odot$ will eject, during the post Main Sequence phase, up to 80% of their initial mass (the fraction increases with mass), passing through the stages of Red Giant and Planetary Nebulae. Star more massive than ~ 7 $M_\odot$ will explode as supernovae producing a large amount of heavy elements (all the atoms heavier than Fe can only be produced by Supernovae). The explosion ejects the largest part of the mass of the stars in the interstellar medium leaving a relatively small fraction (<10 %) of the initial mass in Black Holes or Neutron Stars. In conclusion: the less massive stars last for a longer time, but at the end of their life most of their masses is lost to the cycle. Increasing their masses, stars will last less (life $\propto M_{\odot}^{-3}$), but they increase the fraction of matter returned to the interstellar medium, enriched of heavy elements, to form new generations of stars. Therefore the chemical evolution of the Universe is mainly due to massive stars.

The evolution of the matter ejected by stars (see Evans 1999 for a review) is schematically represented in the right side of fig. 1 (and will be discussed in the following sections). The matter aggregates in Giant Molecular Clouds, which show density enhancements in relatively small, cold regions called ”Dense Cores”. Stars form inside these cores and the mass of the dense cores settles the upper limit of the star masses. The masses of the Dense Cores have a lower limit given by the Jeans Mass (see § 3), that depends on the temperature of the Cores which depends on the cooling capacity of the gas. The cooling capacity of the gas of the Dense Cores depends on the abundance of molecules, like CO, with a dipole momentum that can be excited at very low temperatures (H_2, the most abundant molecule, has only quadrupole momentum).

The abundance of these molecules depends on the heavy elements produced in the previous generation of stars. So the mass spectrum influences the production of heavy elements and the production of heavy elements influences the mass spectrum. In the Early Universe, when heavy elements were not abundant, the gas of the clouds should have been much warmer; the Jeans Mass (§ 3) much higher; therefore stars much more massive than those we have nowadays should have been produced (Stahler, 1986). These first generations of massive stars have rapidly increased the abundance of the heavy elements of the Early Universe.

2 Giant Molecular Clouds

Giant Molecular Clouds (GMC) are large condensations of gas and dust which are detected and mapped at 2.6 mm by the J = 1-0 rotational transition of the CO molecule (Blitz & Williams 1999; Myers 1999). The average properties of GMCs are:

Mass	M	10^4 - 10^6	$M_{\odot}$
Size		10 - 100	pc
Density	N	~100	cm^{-3}
Temperature	T	~ 10	K
Sound speed	c	0.2	km/s
Gas/dust (in mass)		100	
Magnetic field		≤ 10	μG

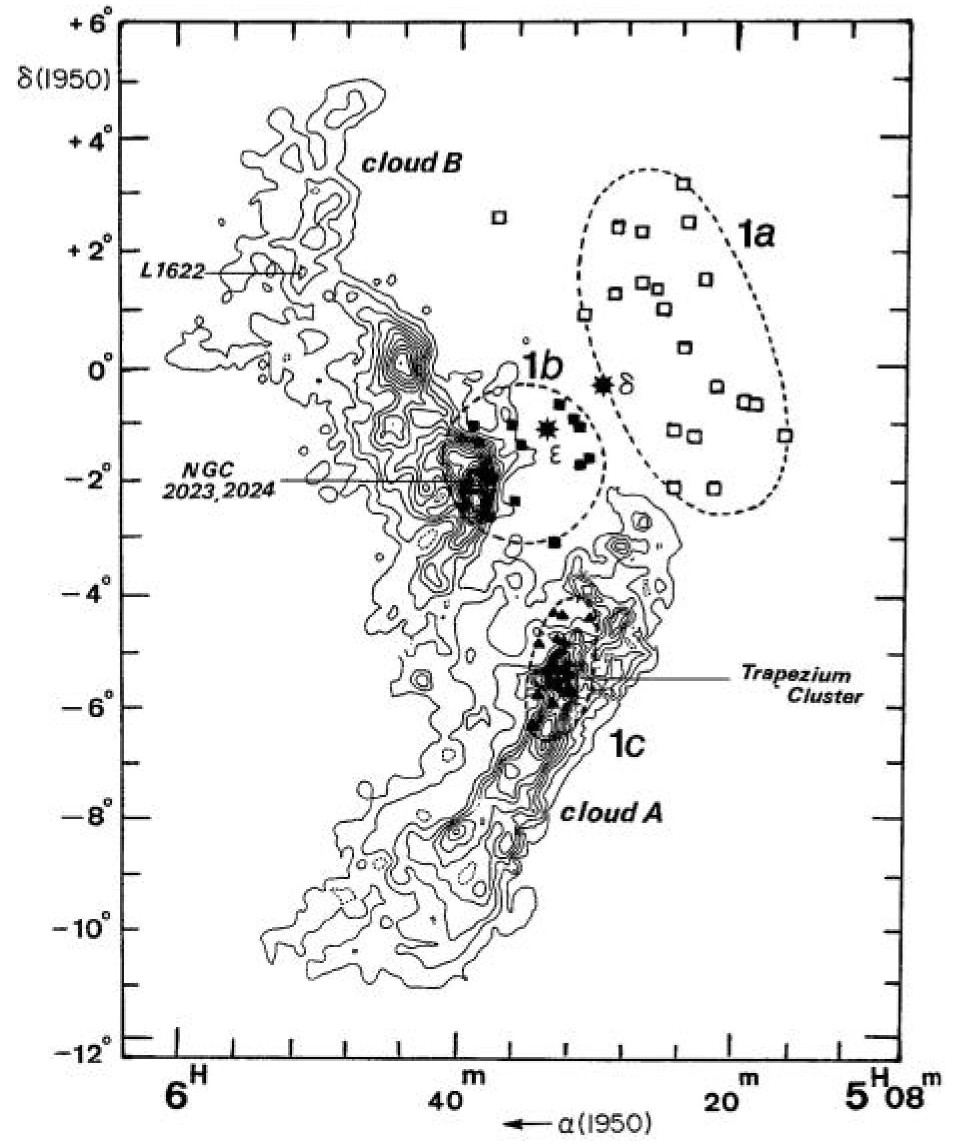


Figure 2: (from Blaauw 1991). The CO map of the Orion cloud (Maddalena et al. 1986) with the subgroup of OB associations formed sequentially.

The major component of GMCs is H_2, but they are detected in the CO line because H_2 (as told above) can not be excited at the low temperature of these clouds. CO is the best tracer of the diffuse medium because it is very abundant ([CO]/[H_2], ~ 10^{-4}), it has a relatively high dissociation energy (11.09 eV) and it can be excited from millimetre wavelengths (few Kelvin) to the near infrared (~ 3000 K) in a variety of different physical environments.

In fig. 2 (from Blaauw 1991), the CO J = 1-0 map of the Orion complex (Maddalena et al. 1986) is shown. The cloud has a total mass of ~ 10^5 $M_\odot$ and if our eyes were sensitive to millimetre wavelength it would be the biggest object of the sky, more than 15 degrees long! The figure shows the typical structure of a GMC, elongated, very inhomogeneous, with density enhancements that always correspond to the star formation regions. The two high density spots of fig. 2 correspond, in the north to the NGC 2023 and NGC 2024 regions, that contain the Horse Head nebula and, in the south, to the Trapezium region with the famous

Orion Nebula. These nebulae are the optical manifestations of light diffused by very luminous (10^4, 10^5 $L_{\odot}$) new formed massive stars, not directly observable in the visible because embedded in the dust. In fig. 3 an optical and infrared image of the NGC2024 region are shown; the brightest of the newborn stars has 10^4 $L_{\odot}$, but it can not be seen in the visible.

Massive stars, once formed, are able to destroy the cloud in a relatively short time. An example can be found in the Orion complex of fig. 2, where Blaauw 1991 recognises three subgroups of sequentially formed stars.

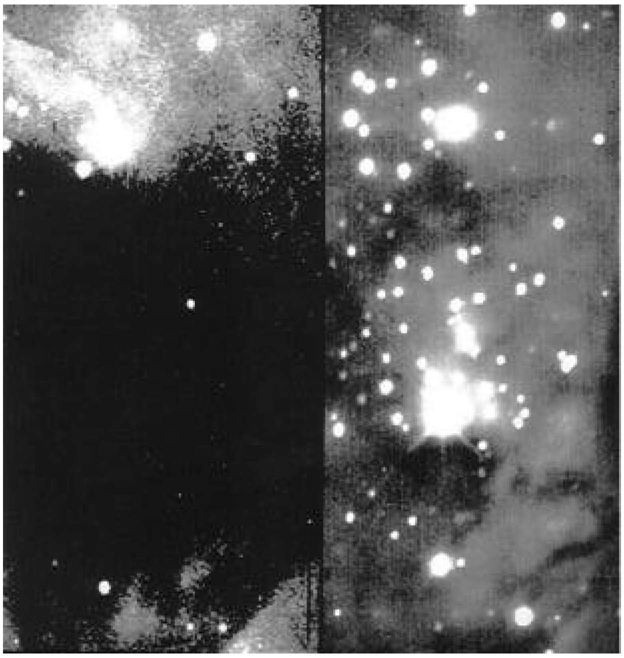


Figure 3. Kitt Peak images of NGC 2024. Left: I band. Right: IR image at 2.2 μm, where a cluster of new formed stars is detected. The brightest IR object has 10^4 $L_{\odot}$

Region 1a) contains the first generation of stars, formed 12 Myr ago: the parental cloud is completely disrupted and the stars appear free from circumstellar material, but still grouped in a cluster that demonstrates their common origin. Region 1b) where star formation is going on since ~ 7 Myr: on the right side of the cloud some new formed stars appear free from the cloud material (among them ε Ori), while others are still embedded at the edge of the cloud (among them NGC2024 of fig. 3). Finally, in 1c), star formation is going on since ~3 Myr and all objects are still embedded in their parental cloud.

The different phases of the evolution of a GMC are schematically represented in fig.4 from Lada (1999). The upper panel represents the first stages: the cloud is very cold and only low mass stars are formed. They have not enough UV photons to create large ionised regions (HII regions). In the warmest regions of the cloud, around the newly formed stars, the gas remains molecular, but hot enough to excite H_2 in the near infrared, H_2O and the high rotational transition of CO in the far infrared, as shown by the data of the ISO satellite (Saraceno et al. 1999). An example is given in fig. 5, where the ISO spectrum of T Tauri is shown.

At some point of the history of the cloud, massive stars (spectral type O, B) form. How they form it is not clear, probably by coalescence of low mass stars, however stars as massive as 120 $M_{\odot}$ (Massey & Hunter 1998) are found in the OB association (Brown et al. 1999). The enormous energy of these objects ($L \propto M^4$) can easily ionise (fig. 4 lower panel) and dissipate the molecular cloud material, stopping the star formation process. It has been shown that ten O stars can ionise and disrupt a mass of 10^4 $M_{\odot}$ (e.g. Franco J. 1993, Whitworth 1979) in a time of $\approx 10^6$ years.

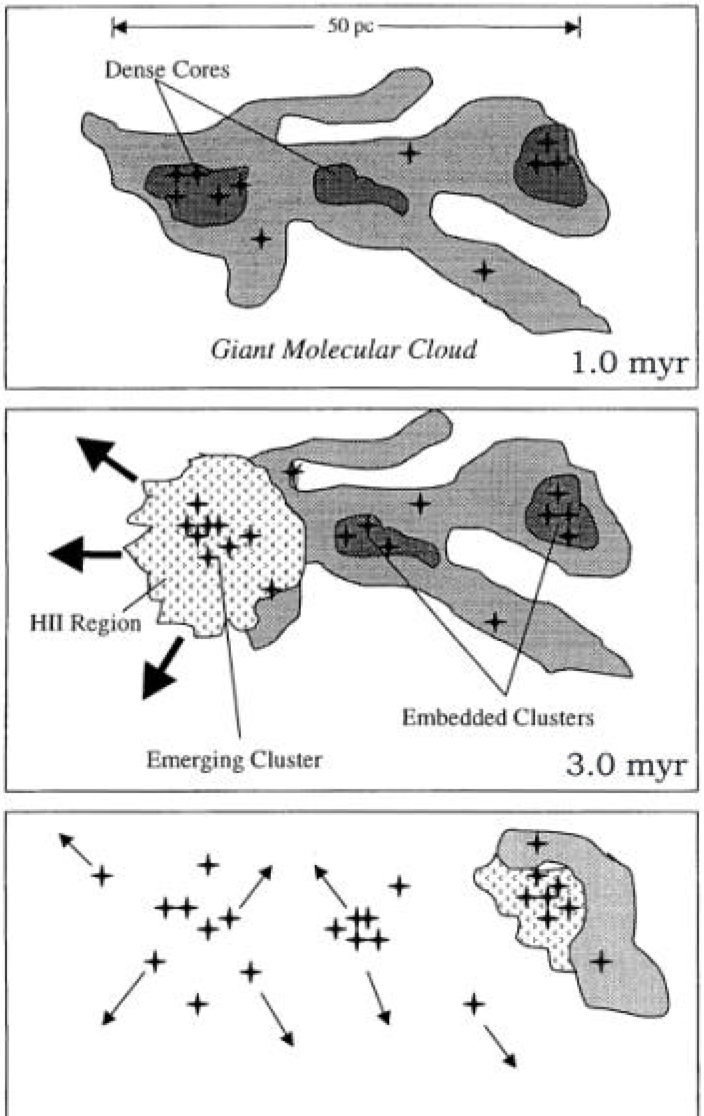


Figure 4: (from Lada 1999). A schematic diagram illustrating the evolution of an OB association.

GMC are generally found near the galactic plane; an overview of their distribution in the Galaxy can be found in Dame et al. (1987). The total mass of the GMCs of our Galaxy is of 3 10^9 $M_{\odot}$ (gas) (Combes 1991) and they form stars at a rate of ~ 3 ±1 $M_{\odot}$/yr (Scalo 1986). This number is very low and shows that

GMCs should have some kind of support against collapse. In fact a GMC, under the effect of gravity, would collapse in a free fall time: $t_{ff} = 3.4 \times 10^7 n^{-0.5}$ yr (Spitzer 1978); with a density n =100 cm^{-3}, we have $t_{ff} = 3.4\ 10^6$ yr.

For a GMC mass of $3\ 10^9\ M_\odot$, this implies a star formation rate of 1000 $M_\odot/yr$, much higher than the observed one!!! The generally accepted explanation is that GMCs are supported against collapse by the turbulence (Zukerman and Evans 1974, Nakano 1998) produced by the outflows that all young stars show. Therefore star formation appears as a self-regulated process: molecular clouds collapse until the number of new formed protostars is able to support the cloud against collapse, then it continues until massive O stars are formed and the cloud will be dissipate.

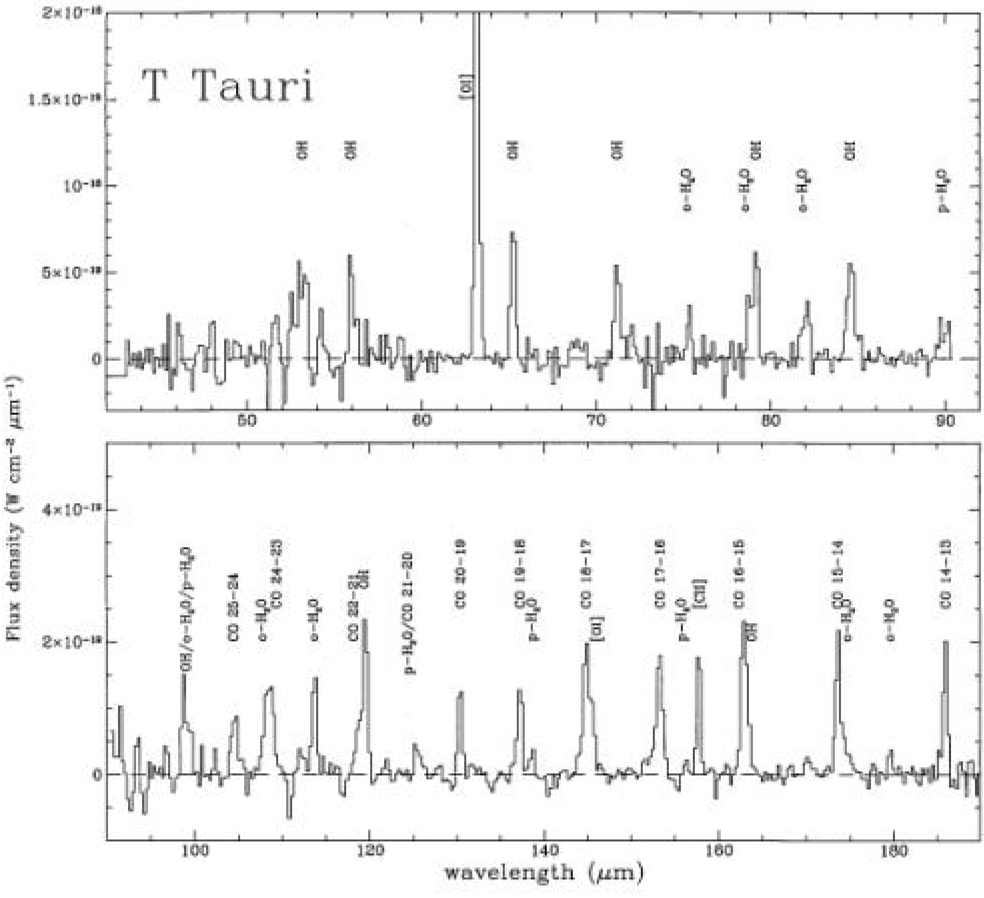
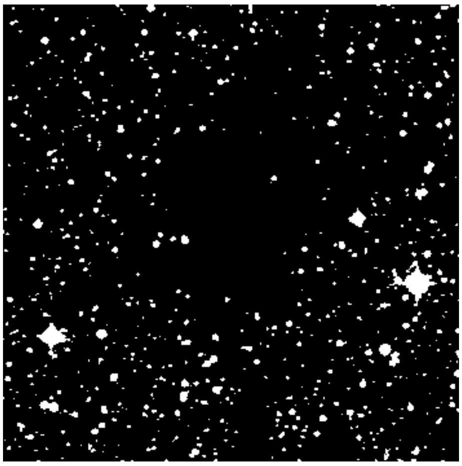


Figure 5: (from Spinoglio et al. 2000). The T Tauri FIR spectrum obtained with ISO shows the major FIR coolants of the gas: CO lines with rotational quantum number ranging from 14 to 25, H_2O and OH.

3 Dense Cores

The small cold and dense fragments of molecular clouds where stars form are called “Dense Cores”. They appear as black spots in the visible because their high density does not allow to see the background stars (fig. 6). They are strong emitters in CO and in other molecules such as NH_3, CS, $C^{18}O$ with a density definitely lower than CO (< 10^{-6} with respect to H_2) which can be detected only at high column densities. These molecules are the tracers of the Dense Cores that, for this reason, have been also called “Ammonia Cores”.

Figure 6. The Bok globule B335 is an example of isolated “dense core”. It is 300 pc distant and hosts a 10 $L_{\odot}$ newly formed star.



About half of the Dense Cores have been found associated with infrared sources (e.g. see fig. 3) exciting energetic outflows. The properties of Dense Cores are (Beichman et al. 1986, Benson & Myers 1989, Myers 1995, Evans 1999):

Mass	M	1 – 10	$M_{\odot}$	(exceptionally 50 $M_{\odot}$)
Size		~ 0.1	pc	
Temperature	T	10	K	
Density	n	10^4 - 10^5	cm^{-3}	
Magn.Field		10 – 50	μ G	
Lifetime		~10^6	yr	(Beichman et al.1986)

The Jeans mass (the minimum mass necessary to keep a cloud bound at a temperature T and density n) computed for the values of the above table gives:

$$M_{jeans}[M_{\Theta}] \approx 40\sqrt{\frac{T^3}{n}} \approx 1-4$$

These values, compared with the masses of the dense cores reported in the above table, show that dense cores are gravitationally bounded and can therefore be considered the first step towards star formation.

About 4.5 billion years ago, at the place of our Sun, there was a cloud similar to the one of fig. 6; all the components from which our solar system and the Earth have been built were contained in the cloud. Most of the water we find on the Earth was probably already trapped in the dust grains of the parental dense cores. Water, in fact, to be formed requires particular physical conditions that can be found in the warm gas (at $T > 350$ K) of the previous generation of star forming regions or on the surface of the dust grains of molecular clouds (Draine et al 1983, van Dishoeck & Blake 1998). The presence of water in the parental cloud of the Sun explains why water is expected (and searched) in all the objects of the solar system (as the polar region of the moon) were water is not evaporated during the hystory of the solar system.

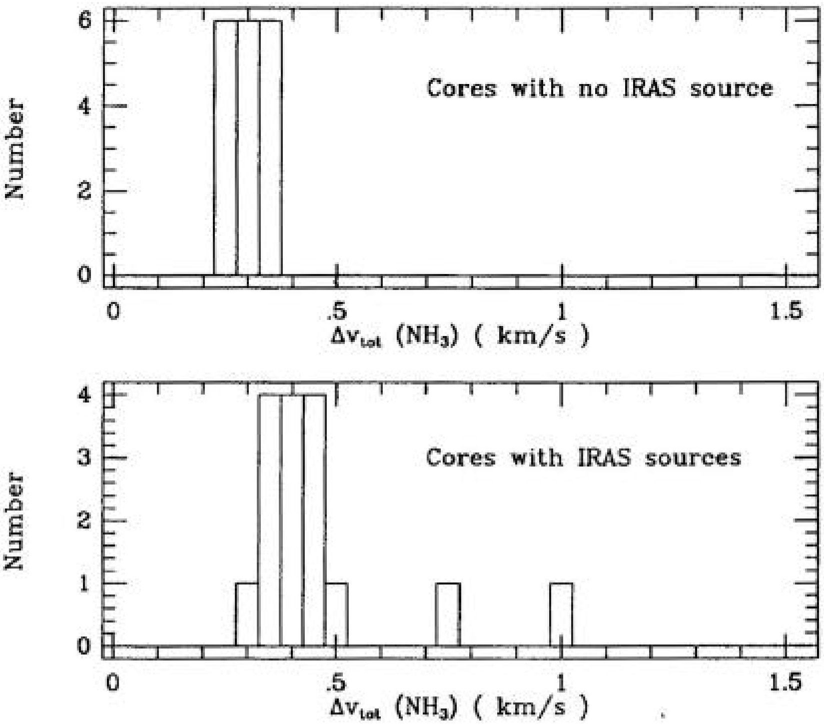


Figure 7: (from Beichman et al. 1986) Histograms showing that cores with IRAS sources (new formed stars) have larger NH_3 line width due to turbulence.

Fig. 7 shows the distribution of line widths observed in dense cores with and without sources detected by the Infrared Astronomical Satellite (IRAS). Cores with new formed stars, detected as infrared sources, have larger line widths (that can not be explained by temperature changes, nearly equal in the two groups), indicating that their outflows are contributing to the turbulence of the Cloud. The outflows of protostars (e.g. Bachiller 1996, Richer et al 2000) are generally very collimated, and they extend to a range of several parsecs, much greater than the dimension of the dense cores. Therefore a large part of their energy is deposited directly in the GMC, giving the necessary support against collapse (discussed in §3).

Beichman et al. (1986) give an estimate of the lifetime of the dense cores, on a statistical basis, by comparing the number of cores of a cloud with the number of the observed preMainSequence stars for which it was possible to estimate the age;

assuming that all dense cores become stars after some time, the lifetime of dense cores has been estimated to be relatively short, of the order of ~10^6 years. This result seems to be confirmed by the recent high-resolution millimetre observations of dense cores, not associated with infrared sources, which show evidence of infalling motion (e.g. Lee et al. 1999).

4 The accretion Phase

To become a star, a dense core has to contract by a factor of ~10^7, from ~ 3 10^{17} cm (0.1 pc) to ~ 7 10^{10} cm, the Sun diameter. This contraction involves mechanisms still poorly understood, like ambipolar diffusion (e.g. Mouskovias 1991; Mouskovias & Ciolek 1999), and dissipation of the cloud turbulence. Only a fraction of the core mass is accreted in the new formed star, the rest is dispersed again in the interstellar medium through outflows and turbulence. The mechanism that fixes the final mass of the star is not well understood. A correlation between the mass function of dense cores and the mass function of stars has been found, but it is generally agreed that the mass spectrum originates inside the individual cores (Williams et al. 1995). The matter to be able to accrete on a star, has to dissipate a large part of its gravitational energy and of its angular momentum. This makes protostars very luminous and the disks, from which planetary systems are built, a natural consequence of the star forming process.

The luminosity of protostars can be evaluated considering that the potential energy to be dissipated to bring the mass M from ∞ to the star radius R is:

$$U = -\frac{3}{5}\frac{GM^2}{R}$$

For masses of about 1 $M_{\odot}$ it can be written as:

$$U = 2\ 10^7\ (M/M_{\odot})^2 \qquad [L_{\odot}\,\mathrm{yr}]$$

A typical timescale for the accretion phase is estimated to be of the order of 10^6 years; therefore the average luminosity of the Sun during the preMainSequence phase (preMS) should have been of the order of ~ 20 $L_{\odot}$, much higher than the present luminosity due to the nuclear reactions. This is an important characteristic of low mass objects: they are more luminous during the preMS phase than during the H burning phase in the Main Sequence (MS). This is even more evident for the less massive objects. In fact, the dependence of the luminosity on mass during MS (nuclear burning) and during the accretion phase, can be respectively written as:

$$L_{nucl} \propto M^4 \qquad\qquad L_{acc} \propto \frac{M}{R}\dot{M}$$

where M and R are the star mass and radius, $\dot{M}$ is the mass accretion rate.

To estimate L_{acc} we need to know the mass-radius ratio M/R and the mass accretion rate. Computations of the mass radius relations in protostars (e.g. Bernasconi & Maeder 1996, Palla & Stahler 1999,) show that M/R changes less than a factor 10 for different masses and different accretion rates. Moreover, also $\dot{M}$ does not vary much inside a cloud and, in first approximation, it depends on the sound speed in the cloud, that is a function of the cloud temperature [Shu, Adams & Lizano 1987]. As an example a star of 0.1 $M_\odot$, has a luminosity of ~10^{-4} $L_\odot$ on MS, while during the accretion phase the same object can have a luminosity of a few solar luminosities (Stahler 1988, Dantona & Mazzitelli 1994). Therefore the accretion phase is today the only possibility to detect the very low end of the mass function.

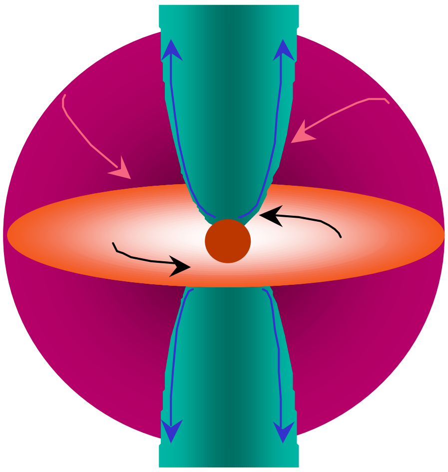


Figure 8: Structure of a protostellar object.

Dense cores rotate very slowly (Benson & Myers 1989), but, with a contraction of a factor 10^7, the rotation can be so fast that the nucleus can fragment in several pieces (explaining why stars belong often to multiple systems), distributing the angular momentum on the different members of the cluster. Disks, which in a later phase will evolve in planetary systems, are also a consequence of this rotation (Jupiter has 98% of the angular momentum of the Solar System) and are formed by the material accreting on the star. The dissipation of angular momentum is also one of the explanations for the energetic outflows that all protostars show. Protostars, being rotating systems, have also a relatively strong magnetic field, therefore outflows have a polar direction along the line of the magnetic field.

A protostar has the structure represented in fig. 8: a central object with a circumstellar disk. The matter coming from an envelope (the dense core) reaches the star dissipating along the disk both angular momentum and energy. Energetic outflows are observed along the polar axis.

The Kuiper belt (100-200 a.u.) and the Oort cloud (0.1 pc) are the residuals of the protostellar disk and of the envelope from which the solar system was formed.

With the time going on the circumstellar material of a protostar is expected to decrease in mass and the protostellar object appears more and more warm.

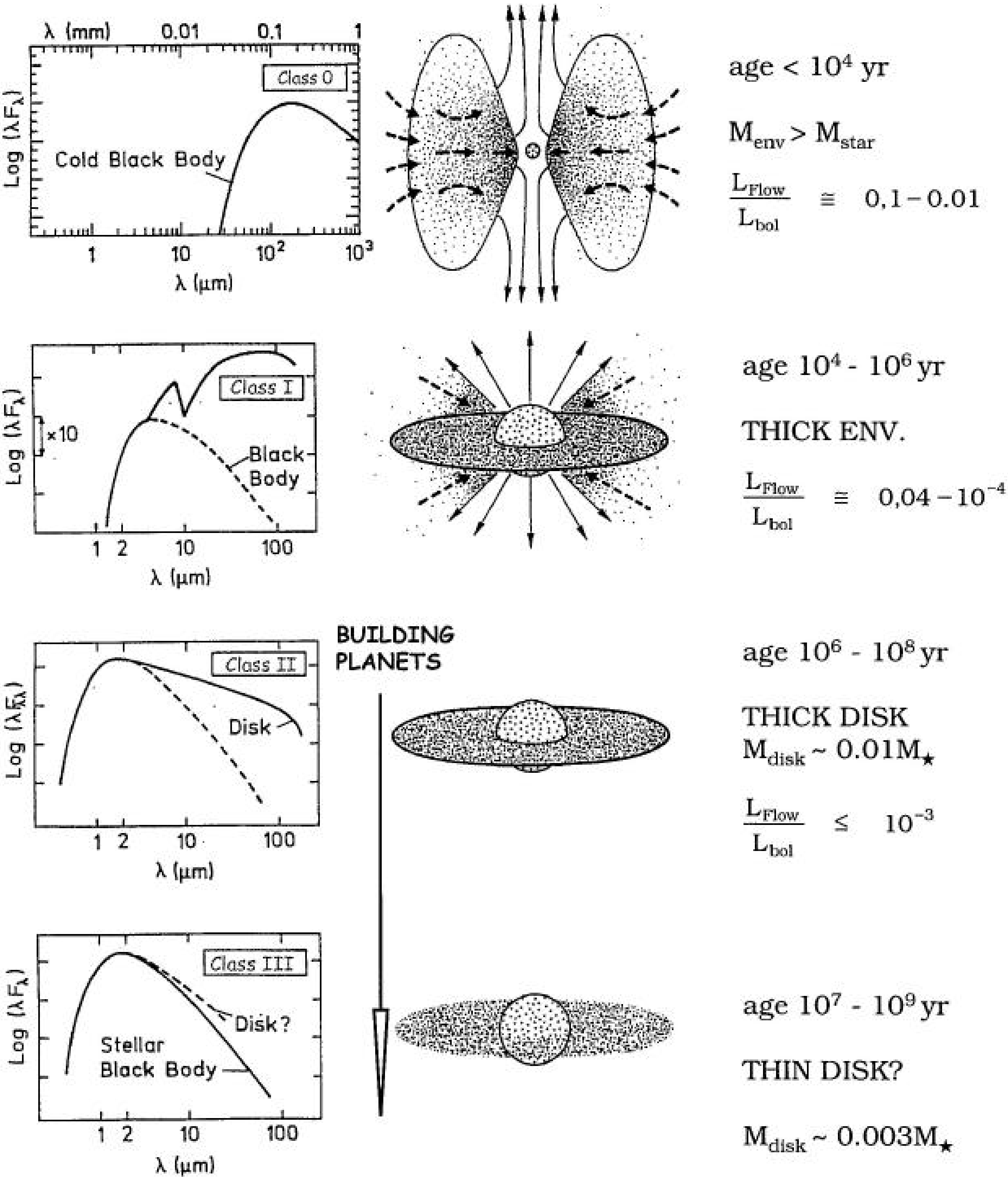


Figure 9: (from André 1994). The evolutionary schema of Low mass stars.

This suggested to Lada & Wilking (1984) to give a first evolutionary sequence of the protostars found in the ρ Ophiuchi cloud, dividing the sources into three classes according to their spectral shapes. Later, the IRAS satellite, that made the first survey of the sky in the far infrared, extended the validity of this classification up to the wavelength of 100 μm, increasing enormously the number of known protostellar and pre-Main-Sequence objects (e.g. Wilking et al. 1989). In 1993 André et al. suggested the introduction of a new class of sources, younger than the objects of the Lada & Wilking classification and so deeply embedded in the parental cloud that they were undetected in the near and middle infrared (often also undetected by the IRAS satellite).

This classification is accepted today for the star forming regions and is schematically represented in fig. 9. From the top to the bottom of the figure, the youngest objects are Class 0 sources, which are thought to correspond to the youngest objects observed with a stellar core. To belong to this group an object has to have an unusually strong submillimetre luminosity compared with its bolometric luminosity, implying a circumstellar mass larger than the stellar mass. The 10 $L_\odot$ embedded source in the B335 cloud (fig. 7) is a Class 0 source. All Class 0 are associated with energetic outflows and they are the objects with the highest ratio between the kinetic luminosity of the flow and the bolometric luminosity (fig. 9). Class I sources have a steeply rising spectrum longward 2μm, generally they do not have an optical counterpart, but they are detected in the infrared.

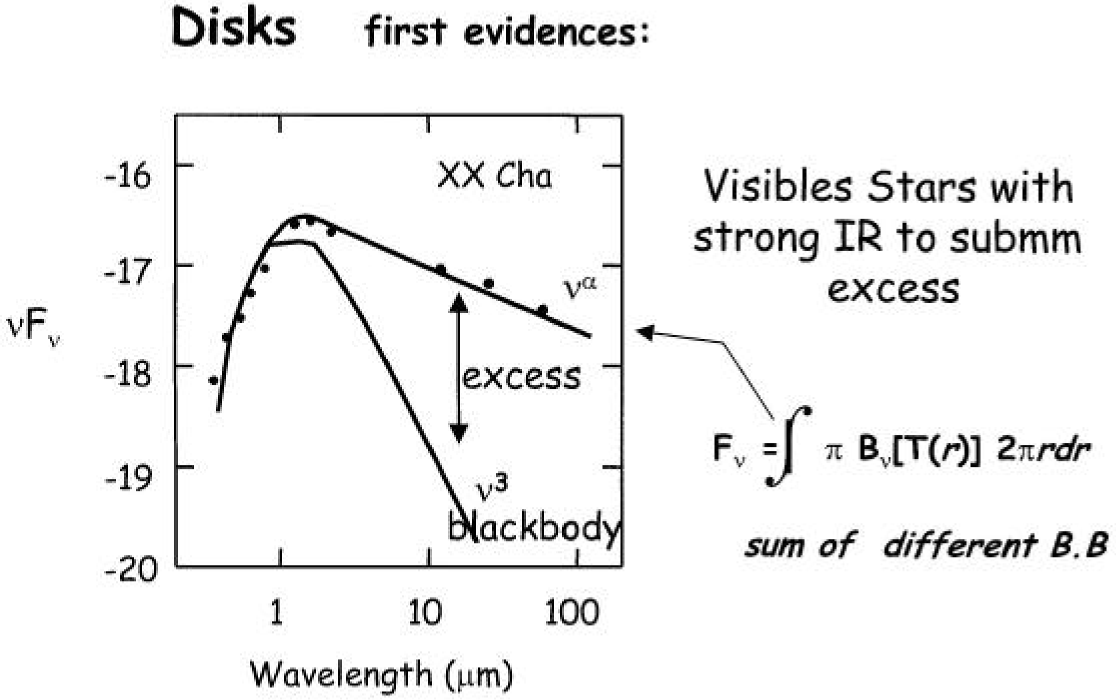


Figure 10 (from Beckwith 1999). Spectrum of the T Tauri star XX Cha, showing infrared to submillimeter excess with respect to the stellar blackbody.

They are generally much more luminous than Class 0 sources and are also associated with energetic outflows. The IR sources of NGC 2024 (fig. 3) are examples of Class I sources. Class II sources have a flat or decreasing spectrum longward 2μm (an example is in fig.10), they are often optically visible sources and excite weaker outflows than the objects of the previous classes. Examples are T Tauri and Herbig Ae/Be stars. Finally Class III sources, exhibiting very weak infrared excess, are considered stars close to the Main Sequence.

5 Disks and Outflows

We introduce here very briefly the problematics related to disks and outflows. To have a deeper overview, we suggest the interested reader a few reviews: Beckwith (1999) for disks, Bachiller (1996) and Richer et al 2000 for outflows.

The first observational evidence of disks has been given by young stars, as T Tauri star, which are strong emitters in the ultraviolet and show a strong excess from IR to submm (fig. 10) indicating the presence in the beam of large masses of dust. Because dust is not obscuring the object in the optical and in the ultraviolet, Lynden-Bell & Pringle in 1974 suggested the explanation that the circumstellar material was distributed on a disk.

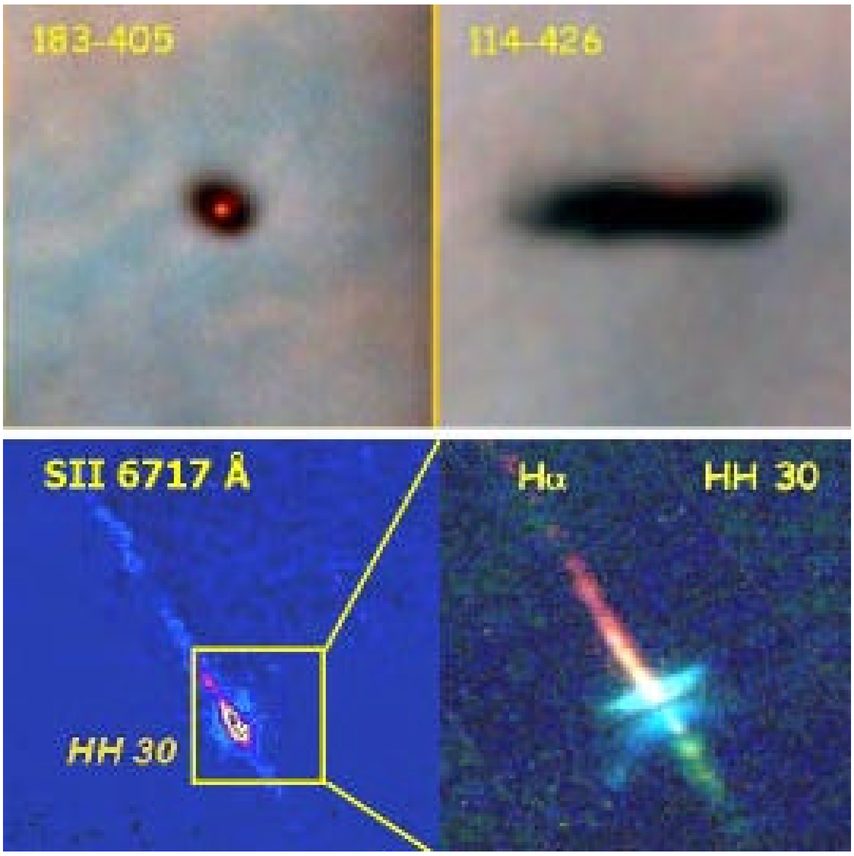


Figure 11. Images of disks a upper panels and of outflows lower panel.

The direct proof of the existence of disks came from the Hubble Space Telescope (HST), which provided their first direct images. Examples are reported in fig. 11. In the upper panels (Mc Caughrean & O'Dell 1996), the silhouettes of disks nebulae illuminated by the background stars are visible in the Orion cloud: on the left, a face-on disk with a new formed star visible in the centre; on the right an edge on disk with the central object obscured by dust. The lower panels show an image of HH 30 in the SII 6717Å line (Mundt et. al. 1990) and in Hα (Ray et al. 1996). Both lines are excited by shocked gas and trace the outflow ejected by the new born star. In the Hα image it is evident the presence of the disk, the black line in the central high luminosity area, orthogonal to the direction of the flow.

Outflows and disks appear well correlated: both appear at the beginning of the protostellar phase and both decrease approaching the Main Sequence. Fig. 11 (Saraceno et al. 1996) shows that the kinetic energy of the outflow of protostars in different evolutionary phases is not correlated with the star luminosity but it correlates with the millimetre luminosity that is proportional to the disk mass. This correlation supports the idea that disks play a direct role in accelerating the flow and that disks and outflows are crucial for dissipating the angular momentum of the accreting material. In order to understand star formation, it is therefore necessary to study stars, disks and outflows as a single system.

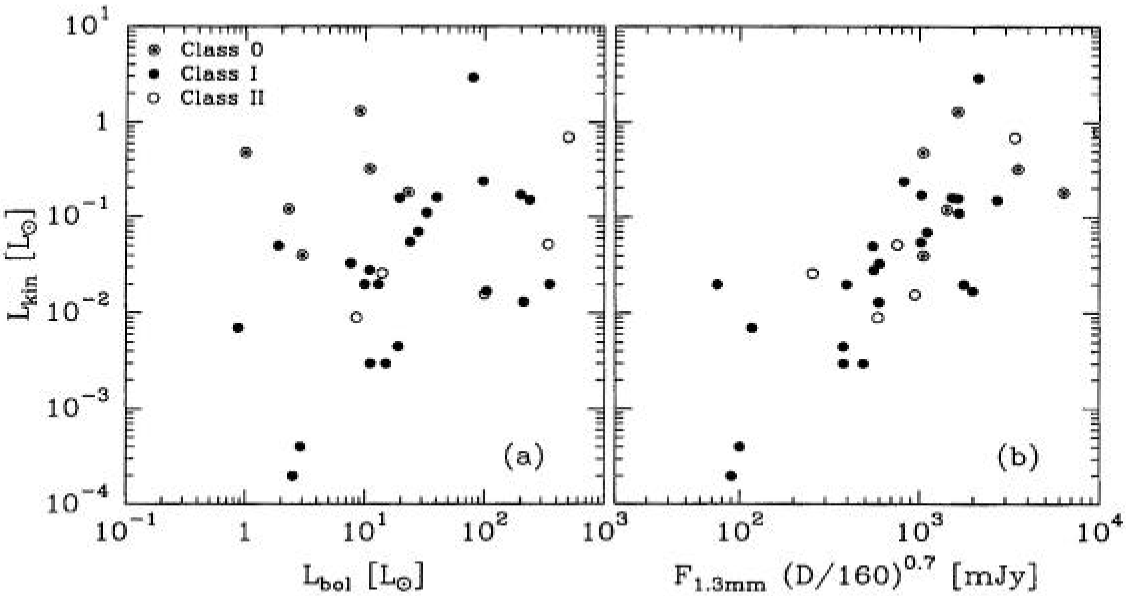


Figure 12: The kinetic energy of outflows correlates with disk mass.

The final phase of star formation (discussed in this conference by Giovannelli) is the one in which the planets are formed. Planets formation is expected to start at the end of the Class II phase (fig. 9), when the accretion phase is close to the end. Fig. 13 (from Beckwith 1999) shows that most of the observed disks can form planetary systems. The figure shows the distribution of the disk masses in the Taurus and Ophiuchus clouds (Beckwith 1990 and André & Montmerle 1994) obtained through millimetre observations. The minimum mass of 0.001 $M_\odot$ that a disk should have to build a planetary system is indicated, together with the mass limits that the theories indicate for the early Solar System. The histogram shows that the disks of the majority of protostars have enough mass to evolve in planetary systems.

The recent discovery by Mayor & Queloz (1995), have shown the existence of planets as massive as 10 Jupiter masses (e.g. Marcy 1999): only a factor 10 below the 0.01 $M_\odot$ necessary for the ignition of H. This suggests that a continuity could be found in the next future between the planets mass distribution and the stellar mass distribution. This will support the idea that very low mass stars are formed as planets of a more massive star (Boss 1995). A proof of this could be the finding of a flat low end of the mass function, because the stars formed as planets should be of the same number of the massive stars around which they form.

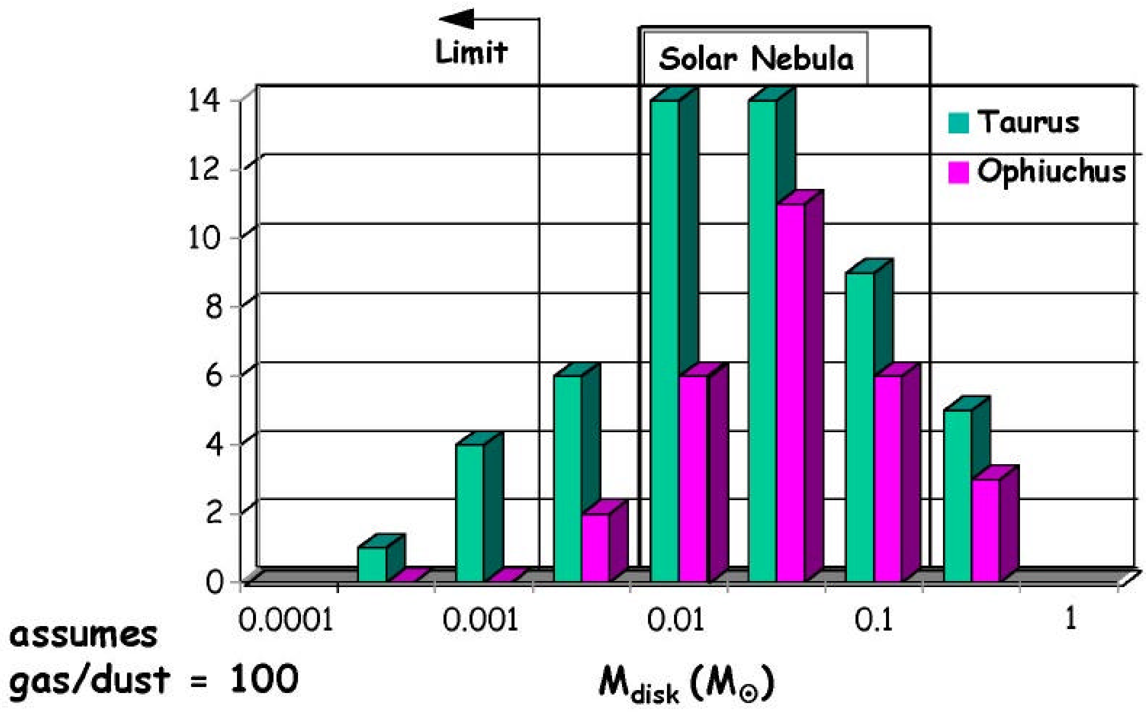


Figure 13: (From Beckwith 1999). The histograms show the distribution of disk masses among stars in the Taurus and Ophiuchus star forming regions.

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