Chapter 1

Introduction

1.1 Star Formation and Near-IR Astronomy

Even as we enter the next millennium, star and planet formation continues to be a challenging problem in astrophysics. The advent of near-infrared focal plane arrays in the last decade made a huge impact on our understanding of the star formation phenomenon. Near-infrared (NIR) cameras have made it possible to study large areas of star forming regions at high spatial resolutions with a high signal to noise ratio. This has resulted in detailed study of many observational aspects of star formation leading to verification of theories of low mass star formation (low mass stars $\sim 1 \, M_\odot$). Recent “All sky surveys” in the NIR bands have also been possible (2MASS, DENIS) due to the availability of large format focal plane arrays, which has resulted in a census of star formation in the clouds of L1630, Taurus-Auriga, Ophiuchus, and several other well known sites of star formation. It is important to note that star forming regions are some of the brightest infrared sources in the sky. Soon after the advent of infrared focal plane arrays, studies of low mass star formation took the first priority in receiving the attention of researchers, mainly because it provides a zoo of observables in the sky. The time scales involved in the formation of a low mass star is of the order of $\sim 10^6$ yrs which makes it possible to catch the various stages of star formation as an observable phenomenon in the sky. In comparison, the high mass star formation is more rapid ($\sim 10^5$ yrs) and it is therefore difficult to observe the various stages of the high mass star formation in the sky. In the last one decade, this resulted in an enormous amount of data to
answer several questions (See Protostars and Planets III, 1993). Having understood fairly well the formation of a single low mass star, further questions arise such as how is it possible to accrete huge amounts of mass involved in high mass stars in such a short time? and what are the processes involved in performing this job? High mass star formation is now turning into a thrust area and will occupy an important position in the area of astrophysics during the next decade (See Protostars and Planets IV, 1999).

Although a satisfactory understanding of the phenomenon of low mass star formation has been achieved, several questions related to circumstellar disks still need to be addressed and the questions regarding formation of planets and young binary companions remain totally unanswered. The sizes of circumstellar disks range from 1-1000AU with ~ 300AU dust disks being common in most cases. A size of 140AU subtends an angle of 1" in the nearest star forming regions of Taurus-Auriga and the details of the dust disks have just been resolved by the HST. The diffraction limit of the HST is not good enough to detect planetary systems around young stars. Until now, most of our understanding of the protoplanetary disks has come through studies by indirect methods like infrared spectroscopy, millimeter and submillimeter wave photometry and recently millimeter wave imaging using high resolution interferometers (e.g. IRAM). These technological developments have also made it possible to address several important questions related to outflows and jets that are ubiquitous with young stellar objects.

The main aim of this thesis is to study the disks and outflows from young low mass stars using the country's first NIR camera PRLNIC. The programs were planned to attempt an understanding of the disk hierarchy which is important in obtaining clues to planet formation. A program to survey for new Herbig-Haro (HH) objects and molecular outflows was initiated and positive results have been obtained (see Chapter 5). The power of both NIR spectroscopy and photometry has been utilised in conducting these studies. Additional data in optical and millimeter wavebands have also been obtained to supplement the infrared data where required. This
chapter briefly reviews the basic physics of star formation and highlights the current problems related to low mass star formation and planet formation with an emphasis on the issues addressed in this thesis.

1.2 Basic Physics of Star formation

Stars form out of huge clouds of molecular gas and dust in the galaxy known as Giant Molecular Clouds (GMC's). GMC's collapse under the influence of self gravity to form stars. The critical condition on the size $R$ (Jeans Length) of a GMC (in thermal equilibrium) with a given mass $M$ to collapse due to self gravity is given by

$$R = \frac{R_g T}{0.4 G M \mu}$$

where $G$ is the gravitational constant, $\mu$ is the mean mass of the molecular species in atomic mass units, $R_g$ is the universal gas constant, and $T$ is the equilibrium temperature of the GMC. Two other forces namely angular momentum of the GMC's and the ambient magnetic field in the GMC's play an important role in the formation of stars. These two forces work against gravity, imposing further restrictions on the critical conditions for collapse. This introduces a magnetic Jeans criterion and a rotational + thermal Jeans criterion that has to be fulfilled before the onset of collapse.

A GMC forms several stars or star clusters. In the process of collapse the GMC fragments into smaller filaments and clumps. The clumps break into several dense cores out of which stars finally emerge. The Jeans criteria described above apply to the collapse process at all levels of fragmentation. In the discussion that follows, we assume a dense core which is a uniform homogeneous mass of gas and dust, with a small amount of rotation and a frozen-in magnetic field. By frozen-in field, one means that the magnetic field and the cloud are interwoven and sustain each other. The magnetic fields in the cold molecular clouds are sustained due to a
small fraction of ionized particles (plasma) mixed with the large mass of neutrals. The fraction of ionized particles are due to the cosmic rays.

Once the Jeans criteria have been satisfied, collapse of the homogeneous dense cores takes a start. We naturally ask the question; how long would it take for a core of mass $M$ and radius $R$ with a gas number density of $\rho$ to collapse to form a star? Using very simple relations $R = ut + \frac{1}{2}at^2$, and assuming an initial velocity $u = 0$ and $a = F/m$ where $F$ is the gravitational force given by $GMm/R^2$, we obtain the free fall time for a particle of mass $m$.

$$t = (G\rho)^{-1/2}$$

that turns out to be $\sim 2 \times 10^6$ yrs for typical densities of $\rho = 10^{-20}$ gms cm$^{-3}$. A more rigorous calculation yields a free fall time given by,

$$t_{ff} = \left(\frac{3}{32G\rho}\right)^{1/2}$$

The above time scales (Dynamical time scales) would be valid if there were no angular momentum and magnetic field coming in the way of gravity. Let us see what does the angular momentum do to the collapse. As the core collapses, the radius keeps decreasing and it is important to follow the behaviour of the different parameters of the cloud as a function of $R$. If we consider the gravitational energy and the rotational energy as a function of $R$, then we will find that the rotational energy increases faster than the gravitational energy (assuming $L$ is constant) which can actually bring the collapse into a halt even before the process is complete. Similarly, if the magnetic flux is conserved the magnetic flux density per unit mass should remain constant in the collapse process resulting in a critical Jeans length that opposes fragmentation. Infact, these problems were well known observationally: the observed magnetic flux density and angular momentum in main-sequence stars are several orders of magnitude smaller than what one would expect to see, if these quantities, originally present in the molecular cloud were to be conserved. We
now know that the magnetic field and angular momentum work towards removing each other in a molecular cloud allowing the collapse process to continue.

Angular momentum is removed from a molecular core by a process called "magnetic braking". The magnetic field lines that are interwoven into the cloud core are connected to the ambient medium (ISM). In the simplest form, this connection results in a restoring force against the rotation of the cloud core, since it would mean rotating the thread like field lines along with the cloud. The actual force is enhanced due to a coupling through Alfven waves and the braking time is given by

$$ t_{braking} = \frac{0.4M}{\pi \rho V_A R^2}; \quad V_A = \frac{B}{(4\pi \rho)^{1/2}} \quad (1.4) $$

where $V_A$ is the Alfven velocity, $B$ is the magnetic field strength, $\rho$ is the external medium density, $M$ and $R$ are the mass and radius of the cloud core. Typical braking times are 5-10 times longer than the free fall timescale. This implies that the process of braking is in action throughout the process of collapse.

The magnetic field in the core is dissipated by a process called "ambipolar diffusion" and is the consequence of rotation. In a spherically symmetric core, the neutral particles are influenced only by the gravitational force and the centrifugal force. However, the ions are influenced by an extra force due to the magnetic field and gyrate along the field lines. Infact, that is how the ions are tied to the field lines and are responsible for sustaining the magnetic field. Removing the ions from the molecular core, therefore, means removing the magnetic field. When such is the case, if $\vec{B}_f$ and $\vec{L}_f$ respectively represent the force due to magnetic field and centrifugal force due to rotation that are orthogonal to each other, then there exists a vector product $\vec{B}_f \times \vec{L}_f$ that acts exclusively on the ions in the outward radial direction of the cloud. While this is happening, the neutrals are still pulled towards the inward radial direction by gravity. This results in a net diffusion of the ions with respect to neutrals and the ions are preferentially removed from the core effectively removing the magnetic field as well. Detailed calculations of such a diffusion time
scale yields a ratio \( \frac{t_{\text{diffuse}}}{t_{\text{dynamical}}} = \text{constant} \approx 8 \). The total time required to remove the entire magnetic field is therefore much longer than the collapse timescale (see McKee et al. 1993, for a detailed review on magnetic braking and ambipolar diffusion).

Under these favourable conditions, collapse process continues to form a star. When matter continues to fall freely towards the center of a spherical core, a radial pressure gradient builds up from the center and the matter at the center falls slowly compared to the matter at the outer regions. This gradient continues to increase until the speed of free-falling material is comparable to or less than the speed of sound in that medium. Once the speed of the falling shells exceeds the speed of sound, a shock front is formed resulting in a surface that isolates a central core from the main spherical cloud core. This state is reached nearly after one free fall time. Material continues to fall through the shock surface into the central core and the pressure builds up again in the central core which continues for another 1.5 times the original free fall time. The \( \text{H}_2 \) molecule starts dissociating in this first core at 2000K and the released energy goes into the pressure gradient within this core. However, since the cloud continues to collapse, a second shock surface forms within the first core, resulting in the formation of a second interior core. The temperature at the core shock surface reaches as high as 20,000K and the hydrogen burning begins at the center of this second core. The dust opacity within this core is about 1 and the radiation gets trapped or thermalized within the core. The material infalling onto this second surface bounces off the core to form the well know “inside out collapse”. This is the state when a pseudo-photosphere (second shock surface) is formed and is identified as a protostar where the luminous energy is derived from the kinetic energy of the infalling matter (Larson 1969 and Stahler et al. 1980).

Two structures, namely the bipolar outflow and an accretion disk, form along with the protostar. First, the material bounced off the core (protostar) is believed to channel-out through the polar regions with the help of magnetic field giving rise to bipolar outflows. Although the theory of outflows is well-understood for the
later stages of star formation (for e.g., T Tauri star phase) it is quite unclear as to its behaviour in the early phases when the central core or protostar is not completely formed. Second, the pressure gradient in the equatorial plane is high due to the centrifugal force resulting in flattened structures that evolve into protostellar disks. The theory of outflows and disk formation is best described in the review article by Shu et al. (1987).

### 1.3 Observational aspects of star forming regions

The zoo of observables within star forming regions has become so vast that it will be impossible to discuss all of them in a single chapter. Rapid understanding during the last decade of the complexity of each phenomenon like GMC's, T Tauri stars and HH objects, has made the task even more difficult. However, a brief outline of the low mass star formation process is given here with an emphasis on the observational aspects, beginning from molecular clouds and ending in the formation of disks and companions. Definitions and terminology that will be used in later chapters are introduced here.

#### 1.3.1 Molecular clouds, clumps and cores

Molecular clouds are best traced by the emission lines of various molecular species present in these clouds. Generally the molecular emission arises due to transitions in the rotational and vibrational levels. Although \( \text{H}_2 \) is the most abundant molecule present in the molecular clouds, it was not detected for a long time. Since the dipole moment of the \( \text{H}_2 \) molecule is zero there is no resulting observable emission due to rot-vibrational transitions. The existence of the \( \text{H}_2 \) molecule in molecular clouds was inferred by Bart Bok (1955), using indirect arguments related to the extinction in dark clouds and the amount of HI emission (see for eg., Elmegreen 1985). Studies of molecular clouds are carried out by observing them in the emission of next abundant species namely CO. A standard \( \text{H}_2/\text{CO} \) ratio is assumed to obtain the
Table 1.2: Physical properties of clouds, clumps and cores.

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Clouds</th>
<th>Clumps</th>
<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass in M☉</td>
<td>10^-2</td>
<td>10^-2</td>
<td>1</td>
</tr>
<tr>
<td>Size in pc</td>
<td>5-10</td>
<td>2-5</td>
<td>0.03-0.1</td>
</tr>
<tr>
<td>Temperature in K</td>
<td>10^4-10^5</td>
<td>10^5</td>
<td>10^4</td>
</tr>
<tr>
<td>Density in cm^-3</td>
<td>10^3-10^4</td>
<td>10^4</td>
<td>10^5</td>
</tr>
<tr>
<td>Emission</td>
<td>10^4-10^5</td>
<td>10^5</td>
<td>10^6</td>
</tr>
<tr>
<td>Magnetic Flux in G</td>
<td>10^-4</td>
<td>10^-4</td>
<td>10^-5</td>
</tr>
<tr>
<td>Trace</td>
<td>100-1000</td>
<td>1000-10000</td>
<td>NH, CS</td>
</tr>
</tbody>
</table>

H₂ mass, CO emission was discovered by Wilson, 1971 near Hill regions and in dark clouds by Penzias et al., 1972. Other important regions of dense regions in the molecular clouds are CH₃CN, OH, H₂CO emitting in sub-mm and sub-millimeter waves. Emission from CO traces the warmer and denser regions of the clouds and that of H₂O traces the colder more regular Table 1.2. It is a direct tracer of the temperature of the clouds. HCl and CO are mainly tracing the densities of these clouds. Table 1.2 also gives properties of different clumps and cores. Dense cores are the inner most part of the clouds. They are not flat and are traced by optically thin NH₃ and CO emission.

An important relationship exists between the size, L of a GMC and the line width, \( \Delta v \) at which it is observed. The relationships obtained by various authors are

\[ \Delta V = 1.15 L^{1/2} \] Damal, 1970

\[ \Delta V = 1.08 R^{1/2} \] Scoville, 1975

\[ \Delta V = 1.65 L^{1/2} \] Solomon, 1987

This result reflects an important nature of the GMC's namely that they are self-similar and are in virial equilibrium. If clouds are in virial equilibrium, then

\[ \Delta V^2 = \frac{3M}{2} \quad L \ll 1 \]

(1.5)

Using \( \Delta V \sim R^{1.2} \) from the above observations, we get \( M \sim R^3 \) which implies that
Table 1.1: Physical properties of clouds, clumps and cores.

<table>
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<th>Cores</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (in $M_\odot$)</td>
<td>$10^3 - 10^6$</td>
<td>$10^3 - 10^4$</td>
<td>$1$</td>
</tr>
<tr>
<td>Size (in pc)</td>
<td>5-20</td>
<td>2-5</td>
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<tr>
<td>Temperature (in K)</td>
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<td>10°</td>
</tr>
<tr>
<td>Density (in cm$^{-3}$)</td>
<td>100-300</td>
<td>$10^2 - 10^3$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>Rotation</td>
<td>$10^{-14}$ s$^{-1}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnetic Flux (in $\mu$G)</td>
<td>30-100</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>Tracer</td>
<td>$^{12}$CO, $^{13}$CO, $^{12}$CO, $^{13}$CO, NH$_3$, CS</td>
<td></td>
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</tr>
</tbody>
</table>

H$_2$ mass. CO emission was discovered by Wilson in 1970 near HII regions and in dark clouds by Penzias et al. (1972). Other important tracers of dense regions in the molecular clouds are OH, NH$_3$, CS, H$_2$CO emitting in the millimeter/cimeter waves. Emission from $^{12}$CO traces the warmer and relatively outer regions of the clouds and that of $^{13}$CO traces the dense inner regions. Since $T_L \sim T_v$ for $^{12}$CO, it is a direct tracer of the temperature of the cloud. $^{12}$CO and C$^{18}$O are useful in tracing the densities of these clouds. Table 1.1 lists typical properties of clouds, clumps and cores. Dense cores are the inner most parts of the collapsing cloud and are traced by optically thin NH$_3$ emission.

An important relationship exists between the size $R$ of a GMC and the linewidth $\Delta V$ at which it is observed. The relationships obtained by various authors are

$\Delta V = 1.20R^{0.4}$ (Dame et al. 1986)

$\Delta V = 0.31R^{0.4}$ (Scoville et al. 1987)

$\Delta V = 1.01R^{0.4}$ (Solomon et al. 1987)

This result reflects an important nature of the GMC's namely that they are self similar and are in virial equilibrium. If clouds are in virial equilibrium, then

$$(\Delta V)^2 = \frac{GM}{R}; \quad \alpha \sim 1$$

Using $\Delta V \sim R^{0.5}$ from the above observations, we get $M \sim R^2$ which implies that

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gas column densities are constant (self-similarity). This property of GMCs depends on the fact that as it breaks into smaller and smaller pieces, the physical nature of the clouds remains the same as it originally was. By observation, it is shown that GMCs are filamentary in nature. One of the important questions that arise if clouds are self-similar then what is the smallest entity in a molecular cloud that finally begins to collapse to form a protostar and what is its size? Recent work by Borrano et al. (1998) and Goodman et al. (1998) has shown that the non-self-similar entity in a molecular cloud is a dense core of sizes $r_0 \approx lpc$ and super cores collapse to form an individual star. Reference to this work will be made in Chapters 4 and 5.

1.3.2 Protostars and T Tauri stars

One of the challenges in star formation studies is to detect the youngest objects possible, so that various phenomena related to the in fall and collapse of molecular clouds can be studied. In an attempt to identify the youth of the candidates for Young Stellar Objects (YSO's), Charles Lada classified them for the first time (Lada, 1984, Lada 1987) based on their spectral energy distribution (SED) in wavebands longward of 2 $\mu$m (see Fig 1.1). This was possible mainly because of the availability of the IRAS data for a large number of protostellar sources. According to his classification, the spectral index defined in the 2 $\mu$m, as

$$\alpha = \frac{\log F}{\log \nu}$$

is positive for the Class I sources, zero or negative for the Class II sources, and negative for the Class III sources. The Class I sources peak at 60-100 $\mu$m and are broader than the black body, with little or no radiation in the near infrared. These objects are also called embedded sources or protostars and are strongly enshrouded by dust. The Class II sources mostly fall into the class of Classical T Tauri stars (CTTS) and have significant IR and UV excess, they have less circumstellar dust and are known to be associated with jets and disks. The Class III sources have a
photospheric emission spectrum close to that of a single black body and there is no evidence for excess iR radiation. These sources mostly fall into the class of Naked T Tauri stars (NTTS) (Walter 1987) and pre-mainsequence stars.

In the study of protostars the presence or otherwise of two important signatures needs to be proved. Firstly, they should be deriving the luminous energy by the infall kinetic energy indicating the extreme youth of the protostar. Secondly, proof has to be obtained for ongoing infall which comes from the identification of an inverse P-Cygni profile of the emission line observed from the source. Recently it has been pointed out by Andre et al. (1993) that the Class I protostars do not actually derive their luminous energy from kinetic energy of the infall. These authors have identified an earlier stage of objects called the Class 0 protostars that derive their luminous energy by the infall kinetic energy and also show strong signatures of infall. One conspicuous quality of the Class 0 protostars is that their submm luminosities (measured at 350\,\mu m) are higher than their bolometric luminosities. This indicates that a large fraction of the mass is still present in the form of infalling dust and gas, that is traced by the submm emission. On the other hand CTTS and WTTS are optically visible stars. CTTS are strongly characterized by their lithium emission line and the "veiling" of the photospheric features in the blue region of the spectrum. In the near-infrared, they have strong Br\,\gamma emission that was thought to arise from disk winds but is now proved to arise from infall in a magnetosphere (Najita et al. 1996)(see Fig 1.3). These stars possess optically thick disks, and are the best candidates to study the dusty circumstellar disks along with associated jets, to obtain an understanding of jet/disk connection. Microjets (Solf 1987) arising from these stars emit strongly in the forbidden emission lines, and are important in the studies of jet/disk relationship. The WTTS are stars with optically thin disks and are believed to have planetary systems that have already formed. These are predicted to be the potential sites to look for new planets.
Figure 1.1: Spectral Energy Distributions of YSO's from Andre et al. 1993
1.3.3  Jets & Outflows from YSO's

The discovery of emission line nebulosities around young stars in the L1630 cloud by Herbig (1951) and Haro (1952) led to the study of mass loss phenomenon in young stars. These nebulosities are now known to be regions of shocked material around young stars and are called the Herbig-Haro objects. It was soon realised that these shocked regions are due to high velocity stellar winds originating from a young star. The discovery of high velocity CO line emission from the nearby molecular clouds and the study of the emission morphology revealed that the high velocity winds associated with the HH objects are traced out by the CO lines and shown to be bipolar in nature (Snell et al. 1980, Rodriguez et al. 1982). Excellent reviews on this topic can be found in Lada (1985) and Bachiller (1996). The different components of the outflow material are traced mainly by emission lines in the millimeter (molecular component), infrared (molecular and optical (molecular component) wavelengths. Most of the mass in the outflow is traced by the strongest lines of CO isotopes indicating that the outflow mass is mainly residing in the molecular component. Generally the outflows are collimated and have standard velocities (a few km/sec to 20km/sec), but there also exist highly collimated, poorly collimated, and extremely high velocity (EHV) outflows (Bachiller 1996). They are generally believed to be driven by highly collimated jets that are seen in near-infrared and optical emission lines. Molecular outflows provide estimates on the mass loss rates from the young star and also an idea of the energy that goes out of the system. The size and velocity of the outflows allow us to estimate the age of these outflows which can then be compared with the age of their driving sources. It has been noticed that the maximum outflow activity is associated with the Class 0 protostars as driving sources (Bachiller 1996).

The optical counterparts of collimated outflows are referred to as jets and were discovered by Mundt and Fried (1983). They are called also as the HH jets since the emission from these jets is similar to that seen in the HH objects. Infact the HH objects are emission nebulosities associated with bipolar outflows, like, the
jets, knots and bowshocks. These objects emit in the emission lines indicative of shocked material, the strongest lines being that of the sulphur [SII] (6717Å and 6736Å) and Hα. Studies of the morphology of jets, their collimation factors (the length to width ratio) can indirectly tell us about the physical processes involved in their formation and collimation. Optical jets have collimation factors ranging from 5 to 30 (see Reipurth 1990). The jets are made up of several knots, working surfaces and they terminate in a bowshock. The knots and multiple bowshocks in a single jet indicate that the mass loss is an episodic phenomenon. The size of the jet combined with its proper motion data allows an estimate of the age of the jet as in the case of outflows. The proper motions also help us understand the homogeneity of the surrounding medium and also the tilt angles of these bipolar outflows. This is due to the fact that the two lobes of the jet/outflow plough into two different media and the way they propagate will tell us about the medium itself. As mentioned earlier, a majority of CTTS have microjets associated with them, that extend from less than 1" to a few arcseconds from the star. Longslit spectroscopy with the slit placed along the outflow axis can reveal these microjets in the forbidden emission lines allowing kinematic studies (Solf 1987, Hirth et al. 1997). Infrared counterparts of HH jets/bowshocks/knots appear strongly in the emission of the shocked molecular hydrogen at 2.122µm and very weakly in the [FeII] emission at 1.645 µm (Davis & Eisloffel 1995). An excellent example of a pulsed near-infrared jet is HH1212 (Zinnecker et al. 1997) which happens to be the best text book example of a near-IR flow. Another class of HH flows identified as giant HH flows or parsec scale flows carry the history of the driving source and its evolution (Reipurth et al. 1998). The parsec scale flows have “S” and “C” shaped symmetries that correspond to the wobbling motion and translation of the driving sources with respect to the parent cloud. Eisloffel & Mundt (1997) have shown similar effects for parsec scale HH jets. Such large scale flows are also believed to pump in a lot of turbulence into the surrounding medium of the young star and may help initiate further star formation.

Figure 1.3: Schematic of an accreting T Tauri Star from Hartmann, L., 1997, in Eds: Reipurth, B., & Bertout, C., IAU 187 Symposium proceedings, Kluwer Pub. Netherlands
1.3.4 Disks and Unified models

The amount of information obtained about mass loss from young stars through studies of outflows have to be understood in an unifying theory that explains disks, jets, winds and the evolution of a protostar. Although it was not possible to spatially resolve the disks until recently by millimeter wave interferometers and HST, their existence was inferred by several indirect methods. Important contributions and surveys were made nearly a decade ago (Beckwith et al. 1990). Several basic properties of the disks like mass, temperature and limits on their sizes were estimated using these earlier methods.

The first important fact that has come through the studies of outflows and protostars is that the energetics involved in outflows and accretion process are comparable. The forbidden line emission associated with the outflows from T Tauri stars is seen only from those stars that have near-IR excess which is attributed to disks (See Chapter 5). Along with outflows that are known to be ubiquitous among YSO’s, disks are also very frequent (80%) in YSO’s. The existence of neutral winds in some sources suggests that outflows may not originate from a hot photosphere but from a disk. It is now fairly clear that the circumstellar disks are the energy storage reservoirs that drive the outflows. Several models have been suggested to explain the star/disk/jet connection and the most popular of them is by Shu et al. (1994) called the X-celerator model (see Fig 1.2). According to this model the jet originates at a boundary layer between the disk and the star called the X point. The energy reservoir is due to the stored magnetic energy, angular momentum and the thermal heating from the UV radiation of the star. The model suggests that the energy is transferred to particles at this point which are then flung outwards along the magnetic field lines. The particles are described to be “beads” guided along the threads of magnetic field lines. The theory became popular ever since X rays were discovered from YSO’s, since the generation of X rays was predicted at the X point. The mass is supposed to continue to accrete onto the star through funnel flows from the disk.
1.3.5 Pre-Main-Sequence Companions

Although it appeared, with the X-celerator model, that there is a unified theory which explained nearly all the observed phenomena of protostars, jets and disks, potential new problems have been pointed out that need to be addressed by theoretical models. It is now well known that nearly 50% of the young stars are binaries (Beckwith et al. 1990). Recent surveys in nearby star forming regions have demonstrated the existence of binaries in young low-mass pre-main-sequence stars. If the young binaries are not identified, then the masses and ages of the binary systems can be substantially misjudged, causing errors in the determination of the Stellar Initial Mass Function and the reconstruction of the star formation history (Zinnecker and Brandner 1997). There have been a class of companions to visible T Tauri stars, called Infrared Companions (IRC’s) (Herbst et al. 1995, Koresko et al. 1997). IRC’s, as the name suggests, are companions which are invisible or just barely visible in the optical and bright in the infrared. Their brightness in the infrared is attributed to ongoing accretion and is proven by the detection of shocked molecular hydrogen emission in their spectrum (see Chapter 5). These facts make it evident that the young companions form prior to the pre-main sequence stage which argues against the random pairing of the field stars and therefore in favour of correlated formation that needs to be explained by models. Further, it is noticed that pairs of non-oriented jets arise from young sources which are putative binaries (Gredel and Reipurth 1993). The misalignment of these jets indicates that the circumstellar disks in binary systems may not always be coplanar. In view of these upcoming evidences, binary formation theories have to be evolved and considerable observational challenges exist in the forth-coming years.
1.4 References

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