THE STAR FORMATION NEWSLETTER

An electronic publication dedicated to early stellar evolution and molecular clouds

No. 6 — 5 Mar 1993 Editor: Bo Reipurth (reipurth@eso.org)

From the Editor

This is a special issue of the Star Formation Newsletter, which brings abstracts of recent Ph.D. theses related to young stars, associated phenomena and molecular clouds. Each of the 18 abstracts in the following pages describe a major effort within its field, and we can during the next year expect to see a host of papers giving details of these exciting results.

Rather than making a yearly issue of Ph.D. thesis abstracts, we will from now on bring such abstracts in the Newsletter whenever a thesis has been accepted. Students who are about to receive their Ph.D. are encouraged to present their work here, and can receive an abstract macro specially made for the purpose by sending me an e-mail.

The Fragmentation of Elongated Clouds and the Formation of Binary and Multiple Systems

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Ph.D dissertation directed by: Pierre Bastien

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The formation of binary and multiple systems through the fragmentation of elongated clouds is investigated. We present three-dimensional hydrodynamic calculations, using a smooth particle hydrodynamics (*SPH*) code, of the gravitational collapse and fragmentation of elongated clouds including rotation either about an axis perpendicular to the cloud's major axis or about an arbitrary axis. The initial cloud parameters are J_0, the ratio of the absolute value of the gravitational to thermal energies, L/D, the ratio of length to diameter of the cloud, and $\beta_{\|}$ and $\beta_{\perp}$, the values of β, the ratio of the absolute value of rotational to gravitational energies, for the component of rotation parallel and perpendicular to the cloud's major axis, respectively. The collapse forms two fragments, one on either side of the equatorial plane. The rotation about an axis perpendicular to the major axis ensures that the two fragments do not collide at the centre of the cloud. A binary system is thus formed. The binary systems have initially high eccentricity and unequal mass systems are possible with slight initial density gradients.

For low values of J_0, the fragments are single and each one is surrounded by a disk. When rotation about an arbitrary axis is included, these disks are parallel but non-coplanar. In this case, interactions at closest approach can be important for dissipating orbital energy.

For higher values of J_0 and $\beta_{\|}$, the fragment plus disk system can subfragment according to one of three modes: Disk Fragmentation involves the fragmentation of a circumfragmentary disk due to tidal forces with the other fragment; Bar Fragmentation is the direct subfragmentation of one of the fragments through an intermediate bar stage; Bar-Arm Fragmentation involves the fragmentation of a bar plus spiral arm. The multiple systems formed through these processes are non-coplanar systems, agreeing with observations that show that at least 35% of multiple systems are non-coplanar.

Gravitational torques and tidal forces play a significant role in the star formation process. Tidal forces in an eccentric system can also be important for enhanced accretion at closest approach. This demonstrates the importance of treating star formation, not as an isolated phenomenon, but in a global treatment incorporating the initial cloud structure and interactions between groups of fragments and stars.

Unequal mass components in a binary system are found to have differing amounts of circumstellar material. This is primarily due to the more massive component being situated closer to the cloud's centre of mass. Observations of pre-main sequence (PMS) stars find that the more massive component is often redder due to circumstellar matter. Many star forming regions are found to contain structures similar to those formed in the numerical simulations presented here.

Cloud dynamics can be used as a diagnostic for where collapse is occurring and whether rotation is involved. The gravitational collapse causes large infall velocities while conservation of angular momentum increases the rotation.

Millimeter and Infrared Studies of Young Stellar Objects in Dark Cloud L1641

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To understand the physical process of star formation, we address three questions: (1) what are the critical indicators of evolutionary states of young stellar objects? (2) when and how are dense cores dissipated? and (3) how are young stars distributed in a single molecular cloud? We selected 224 IRAS sources from the IRAS co-added images in dark cloud L1641. The IRAS data analysis suggested that the 122 sources inside L1641 are probably young stellar objects, while the sources outside L1641 are probably infrared cirrus. In ^{13}CO and HCO^{+} millimeter observations, we found that most of the IRAS sources with CO outflows are associated with molecular dense cores, while most nonoutflow sources are not. This can be explained if dense cores are dissipated by the outflows before the driving sources become pre-main- sequence stars. Using near-IR array detectors, we imaged 59 IRAS sources in H and K', some of them also were imaged in narrow-band L and M. The most result of the imaging is the detection of small groupings of 10-40 near-IR sources near 14 IRAS sources. These groupings, defined as stellar density enhancements (SDEs), are statistically significant compare to background stars. Most of the near-IR sources within the SDEs are low-mass pre-main-sequence stars physically associated with the IRAS sources. The SDEs probably result from pile-up of young stars due to continuous star formation within the dense cores, a phenomenon seen in the early stage of star formation. Our images showed that young stars in L1641 can be characterized by a range of stellar densities, from a large cluster (the Trapezium Cluster) to the SDEs and to individual stars. The previously proposed cluster and isolated star formation modes are probably high- and low-ends of a continuous distribution. With the near-IR imaging, we were able to identify the probable near-IR counterparts for 55 of the 59 IRAS sources. Forty-five of them are class I sources and the other 10 sources are class II sources.

Molecular Hydrogen Line Emission from Photodissociation Regions

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The work presented in this thesis is dedicated to the study of the physical properties of photodissociation regions (PDRs), the surface layers of molecular clouds which are irradiated by ultraviolet radiation. The structure of PDRs is investigated with the development of an anlytical model which incorporates the essential heating and cooling mechanisms in a PDR. The main parameters in the model are the density and the incident ulttraviolet radiation field (G_0) impinging on the surface which dissociates the molecules in the PDR. It is demonstrated that when the ratio (n/G_0) is high ($> 100\ cm^{-3}$) the attenuation of ultraviolet photons is dominated by H_2 self shielding, which brings the HI/H_2 transition zone close to the surface of the cloud ($A_v < 1$). When the ratio is of order unity then the attenuation of ultraviolet photons is dominated by dust grains in the PDR. In this case, the HI/H_2 transition zone occurs at a depth of $A_v \sim$ 2-3.

Images of the PDR in the northern bar of M17 show that there is a spatial coincidence, accurate to $\sim$ 1 arcsec, of the H_2 and 3.28 μm emission regions (the 3.28 μm emission being a tracer of the hot edge of the PDR delineated by the HII/HI transition) placing a lower limit to the density in the clumps of 10^5 cm^{-3}. This coincidence is also observed in other PDR sources (eg. NGC 2023) and can be readily explained if the sources are clumpy. It is not clear in the northern bar of M17, where $G_0 \sim 10^4$, whether shielding by dust or H_2 molecules is dominated the attenuation of ultraviolet photons. A uniform, high density PDR model is sufficient to reproduce the observed H_2 line intensity, however the images clearly reveal structures at the 2 arcsec level suggesting that a clumpy model is a realistic solution.

Long slit K band spectroscopy measurements were taken in the northern bar of M17, where up to 16 H_2 lines were identified. Analysis of the data suggests that the emission can only be explained if the H_2 molecules are being excited radiatively rather than by shocks. The diagnostic line ratio of the H_2 v=1-0 S(1) and 2-1 S(1) transitions is approximately 3 over the region observed implying that the lower levels of the molecule are slightly thermalised by the warm gas. The constancy of the ratio further implies that the collisional deexcitation rate must be constant along this region. This may be taken to mean that the physical conditions do not change along the region and that we are observing the surface of the PDR. The profile of the molecular emission along the slit can be successfully modelled if it is assumed that the large scale surface geometry in the region can be described by a parabola.

The ortho to para ratio of H_2, measured in the three PDR sources (M17 northern bar, NGC 2023 and Hubble 12), is less than the expected value for a hot ($\sim$ 300 K) gas in thermodynamic equilibrium (ie. 3). The measured values fall in the range 1.3 - 2.3. Modelling the orth to para ratio using the rates of spin conversion of the H_2 molecule do not satisfy the observations. Some other form of processing the ortho to para ratio must be occuring and three different models are considered. First, a different reformation mechanism is considered which allows the newly formed molecule to reside on the surface of the grain for a certain amount of time before it evaporates into the gas. The second model describes a dynamic PDR. Hot gas at the surface of the PDR is allowed to escape setting up an advancing photodissociation front. If the front advances into the cooler gas before there is enough time for spin changing interactions to take place, then the measured ortho to para ratios will have values characteristic of the cooler (T $\sim$ 50 - 150 K) gas. Both of these models can successfully reproduce the observed ortho to para ratios. The third model assumes that there is some processing of the ortho to para ratio during the fluorescent cascade, after it has been excited by ultraviolet photons. This model is not successful at reproducing the observed ortho to para ratios as the cross sections in the excited states are so large compared to the radiative decay that the ortho to para ratio is determined at the gas temperature, giving ratios $\sim$ 3.

Column densities calculated from the emission from NGC 2023 has shown an excess of emission above the pure fluorescent cascade in levels which are highly rotationally (J > 5) and vibrationally (v = 3 - 6) excited. In accordance with theoretical predictions, this may be the first direct evidence of the formation of H_2 occuring in excited levels.

The Gould Belt: Structure and Origin

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The structure of the Gould Belt system of young stars and star formation complexes has been studied, mainly through the use of an extended sample of early-type stars. Statistical derivations of some of the most relevant parameters of the Belt (orientation, spatial extent, stellar content, age) are made, and some large scale trends of the recent history of star formation in the solar neighbourhood are discussed. Special attention is paid to the local kinematics of young objects; the local peculiar kinematics as revealed by anomalous values of Oort constants is fitted by an expansion of the local system along a preferential line, superimposed to the general pattern of galactic rotation. Some other regions with anomalous motions are detected outside the Gould Belt, with strong evidences for a moving group possibly related to the Cygnus Superbubble. Dynamics of the tilted plane containing the Belt implies a very constrained range of possible values for its original orientation. Moreover, indications of a vertical oscillating motion of the ensemble of stars in the Belt have been found, the association to the Belt being supported by the fact that both the oscillation axis and the current state of vertical motion relate well to the overall picture of the Gould Belt.

A second part of this work is devoted to a theory on the origin of the Gould Belt. We propose it to have formed from the collision of a high velocity cloud on the galactic disk by the large scale phase transition of the galactic interstellar medium triggered by the colliding cloud. Analytic 1-D calculations provide us with the values of the most relevant quantities involved in the shock. 2-D computer simulations show the morphology of the region affected by the shock. The stability analysis of the shocked material shows that the unstable regions should have characteristics and locations similar to those of currently observed complexes belonging to the Gould Belt. The galactic magnetic field is essential in determining the further evolution of the shocked material. An overall agreement is found between the observation of structures belonging to the Belt and the predictions of our model.

J-Shock Waves with Magnetic Precursors

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Standard models of inter-stellar shocks produce either strong H_2 emission (magnetically controlled C-shocks) or strong optical and UV emission (J-shocks), but not both. Following a brief review of infrared and radio molecular emission of Herbig-Haro objects, a model for a J-shock with a magnetic precursor, which is produced when a shock wave propagates through a magnetized molecular medium, is presented. As part of these calculations, the level population and emission of molecular hydrogen, as well as its destruction by chemical reactions with other particles and dissociation by collision with atomic and molecular hydrogen and electrons, are taken in consideration. In this type of shocks, the H_2 emission (infrared and ultraviolet) arises from the magnetic precursor, while the optical lines are emitted mainly by the gas behind the shock front. The results of this model show that hydrogen molecules radiate a considerably fraction of the total available energy in infrared lines, and that if H_2 molecules reach the J-shock before being dissociated within the precursor, excitation of the Lyman and Werner bands by hot electrons could carry away an amount of energy comparable to that radiated by H_2 infrared lines.

Applying this plane-parallel model to the HH7 Herbig-Haro Object, it is found that this single model seems to explain most of the existing infrared observations of this object. A bow-shaped shock wave model is constructed using several plane-parallel J-shocks with magnetic precursors. This model reproduces with some detail not only the infrared and optical line intensities but also the line profiles, position-velocity diagrams and morphology obtained at optical and infrared wavelengths. Some predictions are made about the intensites, profiles and emission distribution of a number of lines which are likely to be corroborated in future observations. Finally, the plane-parallel models are used to investigate the infrared emission observed in the Cygnus Loop Supernova Remnant.

Proper Motion Measurements of Jets from Young Stars

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The first extended proper motion measurements in jets from young stars are presented. In five well-known jet systems (HH 34, HH 46/47, DG Tau, DG Tau B, Haro 6-5B), consisting of a total of eight optically observable jets and counterjets, as well as of six bow shocks, proper motions of the knots (condensations) have been measured. These measurements are based on deep CCD images, taken through narrow-band filters, which are centred on the Hα or the [SII]$\lambda\lambda$6716,6731 lines. They have been taken on at least three different epochs with a total epoch difference of at least four years. For several observing runs the seeing conditions were excellent ($\approx 0.''6 - 0.''9$).

The proper motion measurements presented allow further principal insights into the physics of the jets and their bow shocks. Among the main results are the following:

- In all eight investigated jets and counterjets the knots are clearly moving. Their tangential velocities reach values from close to the detection limit (≈ 20 km s^{-1}) up to 400 km s^{-1}, with most of the measured values in the range from 100 to 350 km s^{-1}. Please note that the knots are generally interpreted as the cooling regions of oblique, crossing shock waves within the jets.
- For the first time the ratio ζ of the pattern speed of the knots to the fluid speed in the jets is investigated. The measured ζ-values range from 0.2 to 1.0, with most values between 0.4 and 1.0. Values larger than 1.0 are not observed.
- The proper motion measurements put important constraints on the various hitherto proposed jet models: obviously they are in contrary with models of stationary jets, which interpret the jet knots as standing shock waves. Also non-stationary models, in which the knots arise from the interaction of jet material of different velocity, are in most cases not supported by the measured ζ-values. The measurements are, however, in agreement with jet models, which interpret the knots as running shock waves, excited by Kelvin-Helmholtz instabilities along the jet channel.
- In the four Herbig-Haro objects HH 34N, HH 34S, HH 47C and HH 47D, which have been interpreted as bow shocks of jets, the internal flow patterns of the condensations have been investigated. They yield important data for detailed investigations of the complex flow motions in the jet head. The measured flow patterns support the idea, that these Herbig-Haro objects are indeed the bow shocks of the jets.

The Multiplicity of T Tauri Stars in the Star Forming Regions Taurus-Auriga and Ophiuchus-Scorpius: A 2.2 μm Speckle Imaging Survey

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This thesis presents the results of a magnitude limited (K $\leq$ 8.5 mag) multiplicity survey of T Tauri stars in two nearest star forming regions observable from the northern hemisphere, Taurus-Auriga and Ophiuchus-Scorpius. Each of the 69 stars in the sample was observed at K(2.2 μm) with an infrared array camera on the Hale 5-m Telescope at Palomar Observatory and imaged using two-dimensional speckle imaging techniques. Thirty-three companion stars were found with separations ranging from $0.''07$ to $2.''5$; 15 were new detections.

This survey reveals a distinction between the classical T Tauri stars (CTTS) and the weak-lined T Tauri stars (WTTS) based on the binary star frequency as a function of separation; *the WTTS dominate the binary star distribution at the closer separations and the CTTS populate the wider separations.* The cross over occurs near 100 AU, the size typically quoted for a circumstellar disk. It is suggested that the nearby companion stars truncate the amount of material available for accretion and thereby shorten the accretion timescale in multiple star systems. Once accretion has ceased the system appears as a WTTS, accounting for the presence of WTTS that are coeval with many CTTS.

Given the limited separation range of this survey, the rate at which binaries are detected suggests that *most, if not all, T Tauri stars have companions.* The binary star frequency in the projected linear separation range 14 to 225 AU for T Tauri stars (59 $\pm$ 16%) is a factor of 3 greater than that of the solar-type main sequence stars (17 $\pm$ 3%). The observed overabundance of companions to T Tauri stars is proposed to be an evolutionary effect; in this scheme triple and higher order T Tauri stars, which are observed at higher frequencies than for the solar-type main sequence stars, are disrupted by close encounters with another star or system of stars.

Large Scale Observations of the Orion B Molecular Cloud in CO(2-1) and (3-2) with the Cologne 3m-radiotelescope

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The thesis is structured into two parts. The first deals with the Orion B cloud. The subjects of the second are 'Improvement of the Telescope Driving Performance', 'The Terrestrial Atmosphere in the Mm- and Submm-Region', and 'Calibration by Planets'.

Orion B

The analysis of the large scale structure and excitation conditions of the southern part of the giant molecular cloud Orion B was the aim of our multiline study with the KOSMA 3m radiotelescope located on Gornergrat, Switzerland (Winnewisser et al. 1986, 1990). The analysis is based on J=2-1 and J=3-2 ^{12}CO and ^{13}CO data gathered during several observing sessions between November 1990 and January 1992. We used two cooled GaAs Schottky heterodyne receivers built at Cologne with noise temperatures (DSB) of about 400 K.

Fragmentation

The large-scale CO-xobservations of Orion B reveal the fragmented structure on all scales between 0.2 pc (the resolution limit) and the extension of the observed region (8 pc). The overall morphology of the cloud is significantly influenced by the Ib Orion OB association which lies roughly 3 degrees (20 pc) to the west. Its HII-region IC434 lies directly to the west of Orion B. CO-intensities fall off rapidly at the western boundary and the velocity structure is formed by the association. Two dense cores, the southern of which is the famous Horsehead-Nebula, have survived the interaction with the HII-region and protrude out of the cloud into the HII-region.

The clumpiness of the cloud shows up in detail in channelmaps of the ^{13}CO(2-1)-isotope. Measurements of ionized atomic carbon in the infrared at 158 μm show a large-scale distribution of [CII] (Jaffe et al. 1993). Obviously the UV-radiation penetrates deeply into the molecular material again revealing the clumpy structure of this material.

The total mass of the observed part of Orion B is 3150 solar masses, which can be subdivided into 244 clumps by a clump-fitting procedure as described by Stutzki and Guesten (1990, ApJ, 332). The resulting mass spectrum is well fitted by a power-law dN/dM $\propto M^{-\alpha}$ with an index of $\alpha = 1.74 \pm 0.05$ similar to spectra found for other giant molecular clouds. 44% of the total mass of Orion B is found in the five most massive clumps with M>200 solar masses. These clumps are associated with the prominent star-forming regions NGC2024 and NGC2023. The 244 clumps are not gravitationally bound, though the more massive clumps are closer to virial-equilibrium than the less massive ones. The average density of the clumps is 4×10^3 per cubiccentimeter, which is significantly lower than the critical excitation density of the CO(3-2) transition, indicating the presence of unresolved substructures. Measurements with higher resolution should reveal cores with higher densities.

CO Line Comparison

In order to derive the excitation conditions within Orion B we also observed ^{13}CO(3-2) along two stripes at constant right ascension and constant declination. We found the following line ratios, which are rather insensitive to position and also essentially constant across the line profile:

$^{12}\mathcal{R}_{3,2}$ = T(^{12}CO(3-2)) / T(^{12}CO(2-1)) = 1
$^{12}\mathcal{R}_{3,2}$ = T(^{13}CO(3-2)) / T(^{13}CO(2-1)) = 1
$^{12,13}\mathcal{R}_{2}$ = T(^{12}CO(3-2)) / T(^{13}CO(3-2)) = 1.5 - 18

The 'standard interpretation' of CO-data assumes (1) constant excitation temperatures T_{ex} along the line of sight, (2) equal T_{ex} for ^{12}CO and ^{13}CO and (3) equal T_{ex} for all transitions ('thermalization', LTE). Applying this 'standard interpretation' on our data leads to seemingly contradictory results: (1) $^{12}\mathcal{R}_{3,2} = 1$ indicates optically thick and thermalized ^{12}CO transitions, (2) the same is valid for ^{13}CO, (3) according to the standard interpretation a ratio $^{12,13}\mathcal{R}_2 = 1.5$ - 18 means mostly optically thin ^{13}CO emission with optical depths between 1 and less than 0.3 in contrast to the above interpretation. Optical thin ^{13}CO emission would lead to a ratio $^{12}\mathcal{R}_{3,2}$ of more than 2.

These apparently contradictory intensity ratios are not found solely in Orion B: Castets et al. (1990) observed similar ratios of the two lowest CO-transitions in Orion A. They point out that the molecular clouds and their constituents, the clumps, are heated by UV-radiation which leads to temperature gradients within each clump provided they are not heated by internal sources. Gierens et al. (1992) show by theoretical modelling of UV irradiated clumps that the observed line ratios are naturally explained by the temperature and abundance variations in the PDR surface of the clumps.

A publication with more details and analysis of the data is in preparation.

Improvement of the Telescope Driving Capabilities

The telescope slewing and nodding performance, its tracking stability, as well as the overall system stability were improved by exchanging the old command micro against an PC/AT and by implementing a new PI-control loop. Hard- and software were tested in simulation runs in Cologne. Tests with the 3m-telescope show that its driving performance has significantly improved.

The Terrestrial Atmosphere

Observations at 230 and 345 GHz were used together with atmospherical models to derive opacities and extrapolate them to higher frequencies. It was shown that the Gornergrat offers favourable conditions for observations at submillimeter wavelengths during wintertime (Kramer and Stutzki, 1991). Furtheron corrections for different opacities in the two sidebands at selected frequencies were derived and implemented into the calibration procedure.

Calibration by Observation of Planets

Formula to calculate half power beamwidths, main beam efficiencies, and aperture efficiencies from observations of planets were presented, explained, and implemented into an easy-to-use program. A surface accuracy of approx. 42 micrometer rms is consistent with measurements between 88 and 492 GHz.

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Double-Lined Pre-Main-Sequence Binaries: A Test of Pre-Main-Sequence Evolutionary Theory

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This thesis is to test the calibrations of theoretical PMS evolutionary models. We compare the theoretical masses and ages of the components of five double-lined pre-main sequence binaries with the dynamical mass ratios and the assumption of coeval formation of binary components. The spectral types and luminosity ratios of the components are derived from comparisons of selected lines in the observed spectra with synthetic binary spectra created from spectral standards. These are based on echelle observations obtained during 1989-1990. Theoretical masses and ages of the components are obtained by comparing with the theoretical evolutionary models of Mazzitelli and VandenBerg.

All the five binaries have components with theoretical masses and ages consistent with the dynamical mass ratios and the assumption of coeval formation. We find no substantial problems with the relative mass calibrations of the theoretical tracks, nor the assumption of coeval formation of binary components. These hold for binaries with ages ranging from $\sim 10^5$ yr to few times 10^6 yr. Assuming coeval formation of binary components, we compare the ranges of both the theoretical mass ratios and the dynamical mass ratios with the detectable range of dynamical mass ratios. The results show that the ranges of theoretical mass ratios and the dynamical mass ratio are small subsets of the detectable range of dynamical mass ratios. This finding indicates that this analysis is a significant test of the relative mass calibrations of the PMS tracks of Mazzitelli and VandenBerg.

The binary P1540 with age of $\sim 10^5$ yr of age is the youngest in our sample. The maximum age difference for the solutions that have theoretical mass ratios consistent with the dynamical mass ratio is only a few times 10^5 yr. This is small compared to the ages of few times 10^6 yr of the other binaries in the sample. This indicates it is possible that processes such as disk accretion have little effect on the evolution of the binaries after 10^5 yr.

Circumstellar Surroundings of Young Stellar Objects

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The close surroundings of young low mass stars hold a multitude of physical phenomena related to star formation. This thesis presents a set of works on theoretical, experimental, and observational issues connected with these phenomena. After a description of the properties of T Tauri, FU Orionis and Ae/Be Herbig stars, with a particular emphasis on their accretion disks, I study the vertical structure of such disks which results from the radiative transfer and the hydrostatic equilibrium. The energy dissipation comes from both the viscous friction of disk particles accreting onto the star and from the absorption of the stellar radiation. A disk "chromosphere" is shown to result from the grazing stellar radiation. In the following I study the possibility of detecting directly the circumstellar features (disk, binarity, planets, jets,...) thanks to the high angular resolution techniques (adaptive optics and interferometry). I then present the prototype of a coronagraph at high spatial resolution that I designed, modelized, built and tested for that kind of observations. Finally I describe the observations of the young stellar system Z Canis Majoris, which I obtained at the diffraction limit of the 3.6 meter ESO telescope in the near infrared. This object is shown to be composed of a binary system in addition to an elongated disk-like structure perpendicular to the known jet and illuminated not by the central source but by the infrared companion.

[A copy of this thesis (which is mostly in french) can be obtained in binary mode by ftp. There is a file 'these_malbet.tar' in the directory '/pub/publications/' at the FTP node 'gag.observ-gr.fr (IP 130.190.200.11)'. By doing 'tar -xvf these_malbet.tar', you create a directory 'these_malbet/' where there is a 'readme' which gives all information.]

Observations and Models of Shock Structures in Herbig-Haro Objects

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I have studied the optical emission arising from the postshock regions of radiative shock waves in supersonic stellar jets emanating from newly formed stars. I obtained spatially resolved kinematic and emission-line ratio maps of the HH 34, HH 111 and HH 46/47 stellar jet systems using an imaging Fabry-Perot spectrophotometer on the CTIO 4-m telescope. From the observed emission-line fluxes, electron densities and excitation conditions, I have made estimates of the preshock densities, shock velocities, and, in some cases, the preshock magnetic field strengths. The prominent bow shocks at the heads of the stellar jets have been modelled in detail using the J. Raymond (CfA) shock code to construct new grids of planar shock models that were optimized for each system and a simple bow shock model described in Hartigan et al. (1987). The principal results were:

1) All three stellar jets show evidence for multiple ejections, i.e., the flows are non-steady. Bow shocks are observed both far from the stellar energy sources and within the collimated jet regions much closer to the sources. The most prominent bow shocks in all three systems have shock velocities much lower than their space velocities derived from proper motion and radial velocity studies. The observed line profiles in these bow shocks are systematically shifted relative to the rest frames of the stellar sources, indicating that they are moving into preshock media which already have high outward velocities.

2) The prominent working surfaces at the heads of the stellar jets all show bow shock/Mach disk morphologies. Simple ram pressure arguments indicate that the jet material entering the working surfaces is $\sim 10\times$ denser than the ambient media. The one exception is for HH47A, where the preshock medium (the wake of the outer bow shock HH47D) is denser than the incident jet material.

3) Magnetic fields do not appear to play a major role in the dynamical evolution of the outflows, at least in the regions of the outer bow shocks. The magnetic pressures in the preshock regions are only $\sim 10^{-3}$ of the ram pressures. However, the magnetic fields do inhibit the compressions achieved in the postshock regions, extending the cooling distances to resolvable scales.

4) The HH46/47 jet splits into two strands (as observed by Reipurth & Heathcote 1991), whose projected separation increases toward lower velocities. This is the signature of a jet that goes fast down the middle and slow at the edges, and is not consistent with a jet that precesses either ballistically or due to magnetic confinement. The jet appears to be entraining the surrounding material, a conclusion also reached by Chernin & Masson (1991) to explain the bi-polar CO emission associated with the outflow. This provides strong evidence for a common origin to the optical and CO outflows in HH46/47.

Photospheric Analysis of Low Mass Pre-Main Sequence Stars

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The atmospheres of low mass pre-main sequence stars are extremely valuable tools for probing the composition of the star-forming interstellar medium. This thesis investigation uses photospheric abundance analysis techniques to determine metal abundances both for individual weakly active T Tauri stars and the molecular clouds with which these stars are associated. Using the high resolution echelle spectrographs of the Palomar 1.5m and the Las Campanas Observatory 2.5m telescopes, high signal-to-noise ratio spectra have been obtained for 53 low mass pre-main sequence stars in six major northern and southern hemisphere star formation regions. Spectra were also taken of 14 main sequence stars with known effective temperatures and metallicity to serve as spectral standards. Equivalent widths of a large number of Fe I absorption lines have been measured, as well as lines of Ca I, Al I, V I, Ni I, Ti I, K I, and Li I. Temperature-sensitive line ratios of neutral iron and vanadium calibrated against the spectral standards are used to derive effective temperatures for 30 weak-line T Tauri stars, which are much improved over the low resolution spectral classifications found for these objects in the literature. Microturbulent velocities have also been found for 16 of the pre-main sequence stars in the sample. Microturbulence values range from 1.0 km s^{-1} to 3.6 km s^{-1} in these late type young stars.

Using these improved stellar parameters, metallicities of a large number of T Tauri stars have been determined for the first time. Abundance analyses of iron, aluminum, calcium, nickel, and titanium are performed on 30 low mass, pre-main sequence stars. In the star-formation regions of Taurus-Auriga, Orion, Chamaeleon, and Ophiuchus, which each contributed five or more association members to the young star survey, bulk metallicities have been determined. The results indicate that the current metal abundances in these clouds are near or slightly above solar values. Cloud material metallicities are then used to calibrate ultraviolet line-of-sight metal depletion studies for the Orion and ρ Ophiuchi clouds.

The final chapter of this work is a lithium abundance analysis for the entire sample of 53 pre-main sequence stars. Statistics performed on a subset of 37 T Tauri stars without veiling give a mean lithium abundance of 3.60 ± 0.07 on the logarithimic scale relative to $\log N(H) = 12$, and a few stars have derived abundances in excess of 4.0. The *mean* lithium values among pre-main sequence stars are considerably higher than the *maximum* values of 3.1 - 3.2 derived for young main sequence cluster stars, indicating that the processes of lithium destruction are quite rapid for low mass stars during the transition onto the main sequence. Although an appreciable spread in lithium abundances are found among the stars in each pre-main sequence star association, no significant differences in mean or maximum lithium abundances are seen between the clusters.

Infrared Studies of Low Mass Star Formation

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My thesis consists of seven infrared studies of low mass star formation. One chapter describes an all sky survey of young stars in the IRAS Point Source Catalog (IPSC). Three chapters contain studies of the Chamaeleon I star forming region. Two chapters concern star formation in the Chamaeleon II molecular cloud. Finally, one chapter deals with star formation in B209, which is a globule in the Taurus clouds. I will summarize the results of these studies in the above mentioned four categories.

Advanced statistical classification methods have been used to extract a set of 5962 young stellar object candidates from the IPSC. In the selection procedure clustering properties on the sky were used in addition to the usually explored IRAS colours. A performance analysis indicates that in low mass star forming regions 87 % of these objects are indeed young stars.

All IRAS catalogues (IPSC, IRAS Serendipitous Survey Catalog and IRAS Faint Source Survey) have been searched for young stars born in the Chamaeleon I molecular cloud. These studies have led to the discovery of the exciting source of Herbig-Haro objects 49 and 50. Ground-based near-infrared photometry has been obtained for a majority of Chamaeleon I members in order to construct spectral energy distributions. Bolometric luminosities have been estimated for 62 out of the 81 known members to construct a luminosity function (LF). A comparison of the LF with that of the ρ Ophiuchi infrared cluster suggests that star formation has evolved further in Chamaelon I.

Young stars in the Chamaeleon II star forming region have been measured in the near infrared and IRAS data has been extracted in order to construct spectral energy distributions and luminosity estimates. An additional search based on the IRAS data has been performed to find new young stellar object candidates. The spatial distribution of young stars and candidate members shows that star formation is more widespread in Chamaelon II than in the well-studied Chamaeleon I.

A study of star formation in B209 revealed two new embedded sources belonging to the group of young stars born in the Taurus region. This result from a small area of the whole cloud complex suggests that our current sample of embedded objects in Taurus may be severely incomplete. One of the new objects is of sub-solar luminosity, but yet it drives a relatively strong molecular outflow. It is possible that the known sample of luminous embedded sources exciting molecular outflows has a large number of low luminosity counterparts, which are extremely difficult to discover. The embedded sources may thus have a similar kind of luminosity function as the T Tauri stars making them physically more similar to pre-main-sequence stars than to protostars.

(If interested in a personal copy of my thesis, please, contact the above mentioned E-mail address.)

The Chemistry of Interstellar Hydrogen Cyanide: Observations and Theory

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The main results of this thesis are as follows

i) The molecular ion $HCNH^+$ has been detected in the dark cloud TMC-1. This is the first detection of this molecule outside the galactic center. The hyperfine structure has been resolved and shown to be similar to HNC. The analysis of the data has shown that the $[HCNH^+]/[HCN]$ ratio is very high, as compared e.g. to the $[HCO^+]/[CO]$ ratio ($\approx 3\,10^{-2}$ vs. 10^{-4}).

ii) The high $[HCNH^+]/[HCN]$ ratio could be successfully reproduced by gas phase chemical models. The best agreement with observations is achieved in models with a very high metal depletion ratio ($[M]/[H] \approx 10^{-11}$), consistent with the non-detection of silicon bearing species in this source.

iii) The source OMC-1 has been mapped in HCN, HNC and some isotopomers with the IRAM 30 m telescope. The derived [HCN]/[HNC] and [DCN]/[HCN] ratios differ drastically from the hot core region to the ridge. HNC and, to a lesser degree, DCN, seem to avoid the star forming region around the infrared source IRc2, while they trace nicely the filamentary structure in the north of the hot core. But even in the ridge, the [HCN]/[HNC] ratio is significantly different from that of a dark cloud. The [DCN]/[HCN] ratio there is surprisingly high, given the kinetic temperatures of about 40 K and densities of about $10^6\,cm^{-3}$.

iv) Complementary, the hot core region was observed with the Plateau de Bure Interferometer in the $HC^{15}N$(1-0) transition. It has been shown, mapping for the first time an optically thin transition in the millimeter–range, that HCN is concentrated on the hot core. The simultaneously obtained continuum data allowed a H_2 column density determination in the hot core. The HCN abundance has been derived to be about 100-300 times higher than in the ridge. A comparison with a BIMA DCN(1-0) revealed that the [DCN]/[HCN] ratio is about 10 times lower than in the ridge.

v) Chemical modelling showed that the ridge results for the [HCN]/[HNC] ratio can be successfully modelled by means of steady state gas phase chemistry of warm, dense gas. The most important assumption in this model is that HNC can be destroyed at high temperatures in reactions with atomic oxygen. The high [DCN]/[HCN] ratio could be explained without further assumptions to be due to neutral–neutral reactions which play no role in less dense gas. By investigating gas phase chemistry with CNO depletion (to model regions where the the gas freezes out onto grains), it could be shown that CNO depletion larger than about 100 (relative to solar abundances) can definitely be ruled out. The observed HCN abundance seems to favour models with a higher [C]/[CO] ratio than predicted by standard models.

vi) The extremely high [HCN]/[HNC] ratio in the hot core could be due to influence of magnetohydrodynamic shocks or due to release of grain–surface chemistry processed ice mantles. While the results of our shock chemistry models predict a [DCN]/[HCN] ratio which is close to thet observed, the grain surface chemistry models from the literature would give ratio which is much too high. A realistic model of the region should therefore allow for both processes taking place, i.e. postprocessing of the released molecules.

A Multiwavelength Observational Investigation of Herbig-Haro Objects and their Exciting Stars

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Herbig-Haro objects are small optical emission line nebulae, shock-heated by collimated winds from young stars. In this thesis, near-infrared imaging and high-resolution [S II] Fabry-Perot imaging spectroscopy have been used to investigate Herbig-Haro object shock structure. Four objects have been studied: HH 7-11, HH 12, HH 34, and HH 1. By a detailed comparison of emission line images and spatially complete kinematic maps, we find that although no single flow model can be applied to all regions, some regions do fit the existing models quite well. HH 7 is well-described as the working surface of a stellar jet, with both a bowshock and a jet terminus shock identified within it. The density of this jet is shown to be comparable to the density of the medium it is impacting. Based on the absence of 2 μm H_2 line emission in the shocked wind material, H_2 does not appear to be a major constituent of the outflowing winds. Within HH 7-11 and HH 12, [S II] radial velocities are lowest at the locations of bright H_2 emission. The [S II] kinematics and H_2 morphology of HH 12 argue for SVS 12 as this object's exciting star, a conclusion which suggests that the observed proper motions in this object represent pattern motion rather than a material velocity. The 1.64 μm [Fe II] emission line has been imaged for the first time in HH objects. The [Fe II] images indicate extinction is not significant in determining the optical appearance of the HH objects studied, and thus the HH 34 bipolar outflow is indeed a one-sided jet system. The spatial distribution of [Fe II] emission correlates well with that optical [S II], indicating that [Fe II] should be an excellent tracer of low-velocity shocks in obscured regions.

The second part of this work is a study of the circumstellar material of two HH object exciting stars using millimeter-wave interferometry. High resolution ^{13}CO images suggest that the HH 34 and HH 111 exciting stars both possess circumstellar disks elongated perpendicular to the highly collimated optical jets emerging from these two sources. The masses of these disks are two to four times greater than the largest disk masses associated with T Tauri stars, although the sizes are comparable. The stellar source masses are most likely less than 2 $M_{\odot}$. From a compilation of interferometer data on different YSOs, it is argued that that HH exciting stars represent an earlier stage of stellar evolution than T Tauri stars, and that large disk masses are being accreted onto the central star, dispersed by the outflow winds, and/or formed into planets during the earliest phases of the life of a star.

Near and Far Infrared Observations of Protostars and Dark Clouds

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Far infrared point source and extended emission data from the Infrared Astronomical Satellite (IRAS) survey are used to investigate the properties of star formation in the regions of high galactic latitude dark cloud complexes. The properties of individual sources are examined using near infrared spectroscopy and broad band spectral energy distributions.

The IRAS signature of star formation is derived by comparing the far infrared colours of a sample of protostars with those of other common far infrared objects. The quality of the IRAS data is ignored for the purposes of this investigation. The criteria developed for identifying protostars from the IRAS Point Source Catalog discriminates against most non-protostellar objects, with the exception of galaxies and HII regions. Objects identified as protostellar according to other criteria are also likely to be identified by the criteria developed.

Extended emission data in the far infrared is used to estimate the column density and temperature of several dark cloud complexes, and the optical extinction in the same regions is estimated with the Guide Star Catalog. Temperature and column density share an inverse relationship: cloud cores are characterised by column densities above 10^{24} hydrogen atoms m^{-2} and temperatures around 20 K, while the inter-cloud medium has column densities below 10^{23} atoms m^{-2} and temperatures above 50 K. The column density, as measured by IRAS, and the optical extinction appear to be related up to values of around 10^{25} atoms m^{-2} and 5 magnitudes respectively, but the IRAS detectors appear insensitive to material at higher densities than these.

Near infrared spectra of a variety of objects chosen for their youth, including IRAS sources which satisfy the protostar criteria, are investigated. These spectra are categorised into three distinct groups of increasing youth:

1. T Tauri-like spectra, with flat H and K band continua, lacking both Br-γ emission and CO absorption;
2. FU Ori-like spectra, with CO absorption, 1.9 μm water absorption, and possibly Br-γ emission, and
3. embedded protostar spectra, with red continuum, and perhaps Br-γ emission, but lacking CO absorption.

The spectral energy distributions (SEDs) of the sources are also investigated, using data at wavelengths from 0.3 μm to 100 μm. All of the objects studied in the near infrared have SEDs characteristic of either T Tauri stars or of embedded protostars. There seems little correlation between the evolutionary status assigned to an object on the basis of its SED and that assigned from near infrared spectral features, perhaps because the shape of the SED is independent of the evolution of the central object, and depends on geometric considerations such as the orientation of the circumstellar disk in relation to the line of sight from the Earth.

Shells, Outflows and Star Formation in the Giant Molecular Cloud Monoceros R2

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To improve our understanding about giant molecular clouds (GMC) associated with R-associations, a CO map of $167,000$ spectra with 45" resolution and 25" spacing, a $^{13}CO\ J = 1-0$ map of $\sim 40,000$ spectra with 1.5' resolution and 1' spacing, *IRAS BIGMAP* images, and maps of high density molecular tracers for the dense cores are obtained for the GMC Monoceros R2 ($D = 830 \pm 50\ pc$).

These data reveal that the large-scale structure of Mon R2 is dominated by an expanding bubble shell ($\sim 30\ pc$) with front side moving towards us at a radial velocity of $\sim 4-5\ \mathrm{km\,s^{-1}}$. Distortions of this shell are obvious, suggesting of the inhomogeneity of the cloud before the formation of the bubble. There is no evidence for red-shifted shell at the far side of the bubble. There are at least two generations of star formation in Mon R2. The older generation of stars with an age of $6-10 \times 10^6$ years are represented mostly by reflection nebulae. The younger generation of stars with an age of $\sim 10^5$ years are represented mostly by *IRAS* point sources. It is proposed that the large-scale expanding bubble shell is the result of combined effects of ionizing flux and stellar winds originating from the older generation of young stellar objects, but perhaps dominated by O type stars which either are obscured or left main sequence. It is proposed that the formation of the younger generation of stars has been triggered by the older generation of stars.

The two well-known star-forming cores, the main core and the GGD12-15 core are located on the large-scale expanding shell. They harbor both generations of stars, which can be explained were the cores preexisting clumps. Our CO data also reveal an eggplant-shaped bipolar outflow shell associated with the central infrared star cluster in the main core. It is shown that the shape of the outflow shell can be satisfactorily modeled with radially directed stellar winds sweeping up ambient material with momentum conservation (Shu *et al.* 1991).

An inversion method is implemented for analyzing dust emission spectra at FIR wavelengths in terms of a continuous dust temperature distribution, and has been applied to *IRAS BIGMAP* images of Mon R2. Computer programs are developed for identifying clumps and determining their properties from the 3-D molecular emission data. The results support the reality of size-linewidth and mass-linewidth relations for clumps in individual GMCs.

Star Formation in Small Molecular Clouds - A Characterization of Young Stellar Objects In Bok Globules: Infrared Imaging, Spectral Energy Distributions, and Molecular Outflows

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This dissertation presents a large-scale observational study of star formation in Bok globules.

A sample of 248 optically selected, small molecular clouds (mostly Bok has been probed using *IRAS* co-added images to search for associated young stellar objects (YSOs). Fifty-seven of the globules show evidence for a total of 72 point sources near locations of local dust heating.

A sub-sample of 41 globules was observed, in the CO $J = 1 - 0$ line, to search for molecular outflows associated with the YSOs. Outflows were found in about one-third of the sample (14 of 41). The presence of an outflow was found to be correlated with the value of the *IRAS*-based spectral index (between 12 and 25 μm) of the YSOs.

A near-infrared imaging survey of 34 globules containing YSO-candidates was conducted in the J, H, and K bands using infrared arrays. Eleven YSO-candidates displayed near-infrared nebulosities. This group of objects, when ordered by their values of the 12/25 μm spectral index, seems to form an evolutionary sequence, from younger objects with negative (red) indices and whose nebulosities are brighter in the K-band, to objects in later stages of pre-main-sequence evolution with positive (bluer) indices and whose nebular emission is brighter in the J-band. Comparison of the morphology of the infrarednebulae with the corresponding CO outflow morphology supports the idea that infrared reflection nebulae, seen at 2.2 μm, are good morphological tracers of CO mass outflow, and that CO outflows occur during the earliest YSO phases.

Photometry of the near-infrared counterparts of the YSO-candidates was combined with their *IRAS* fluxes to yield broad-band spectral energy distributions (SEDs). The broadness and steepness of the SEDs indicated clear evidence of the evolutionary stage of the objects, confirming their youth.

Given all of the new information obtained, a firm conclusion emerged, namely that Bok globules are active sites of low-mass star formation.