Abstracts of recently accepted papers

The Formation Mechanism of Brown Dwarfs

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We present results from the first hydrodynamical star formation calculation to demonstrate that brown dwarfs are a natural and frequent product of the collapse and fragmentation of a turbulent molecular cloud. The brown dwarfs form via the fragmentation of dense molecular gas in unstable multiple systems and are ejected from the dense gas before they have been able to accrete to stellar masses. Thus, they can be viewed as 'failed stars'. Approximately three quarters of the brown dwarfs form in gravitationally-unstable circumstellar discs while the remainder form in collapsing filaments of molecular gas. These formation mechanisms are very efficient, producing roughly the same number of brown dwarfs as stars, in agreement with recent observations. However, because close dynamical interactions are involved in their formation, we find a very low frequency of binary brown dwarf systems ($\lesssim 5\%$) and that those binary brown dwarf systems that do exist must be close $\lesssim 10$ AU. Similarly, we find that young brown dwarfs with large circumstellar discs (radii $\gtrsim 10$ AU) are rare ($\approx 5\%$).

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IRAS 21391+5802: The Molecular Outflow and its Exciting Source

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We present centimeter and millimeter observations of gas and dust around IRAS 21391+5802, an intermediate-mass source embedded in the core of IC 1396N. Continuum observations from 3.6 cm to 1.2 mm are used to study the embedded objects and overall distribution of the dust, while molecular line observations of CO, CS, and CH_3OH are used to probe the structure and chemistry of the outflows in the region. The continuum emission at centimeter and millimeter wavelengths has been resolved into three sources separated $\sim 15''$ from each other, and with one of them, BIMA 2, associated with IRAS 21391+5802. The dust emission around this source shows a very extended envelope, which accounts for most of the circumstellar mass of 5.1 $M_\odot$. This source is powering a strong molecular outflow, elongated in the E–W direction, which presents a complex structure and kinematics. While at high outflow velocities the outflow is clearly bipolar, at low outflow velocities the blueshifted and redshifted emission are highly overlapping, and the strongest emission shows a V-shaped morphology. The outflow as traced by CS and CH_3OH exhibits two well

differentiated and clumpy lobes, with two prominent northern blueshifted and redshifted clumps. The curved shape of the clumps and the spectral shape at these positions are consistent with shocked material. In addition, CS and CH$_3$OH are strongly enhanced toward these positions with respect to typical quiescent material abundances in other star-forming regions. These kinematical and chemical evidences suggest that the clumps are tracing gas entrained within the surface of interaction between the molecular outflow and the dense ambient quiescent core, and that the morphology of the molecular outflow is a result of this interaction. The circumstellar mass together with the power-law index of the dust emissivity measured, $\beta = 1.1 \pm 0.3$, and the fact that the source is driving a molecular outflow are consistent with the source BIMA 2 being an embedded intermediate-mass protostar. In addition, thesource fits very well correlations between source and outflow properties found for low-mass Class 0 objects. The other two sources in the region, BIMA 1 and BIMA 3 have a mass of 0.07 $M_\odot$, and their dust emissivity index, $\beta < 0.3$ and $\beta = 0.1 \pm 0.3$, respectively, is consistent with more evolved objects. BIMA 1 is also driving a very collimated and small bipolar outflow elongated in the N–S direction.

N$_2$H$^+$ and C^{18}O Depletion in a Cold Dark Cloud

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We present sensitive, high angular resolution molecular-line observations of C^{18}O and N$_2$H$^+$ toward the dark globule B68. We directly compare these data with the near-infrared extinction measurements of Alves, Lada, & Lada (2001) to derive the first evidence for the depletion of N$_2$H$^+$, and by inference N$_2$, in a pre-stellar dark cloud. We also find widespread C^{18}O depletion throughout the centrally condensed core of the B68 cloud. Specifically, we find the N$_2$H$^+$ emission to peak in a shell partially surrounding the peak of dust extinction. Moreover, the N$_2$H$^+$ peaks inside the much larger C^{18}O depletion hole and has a smaller depletion zone, confirming theoretical predictions. These data are analyzed through a direct coupling of time dependent chemical models to a radiation transfer code. This analysis highlights the importance of photodissociation at cloud edges and suggests that the CO abundance declines by two orders of magnitude from edge to center. In contrast N$_2$H$^+$ declines in abundance, at minimum, by at least a factor of two. Indeed it is entirely possible that both N$_2$H$^+$ and N$_2$ are completely absent from the central regions of the B68 core. The depletion of N$_2$H$^+$, and its parent molecule N$_2$, opens the possibility that the centers of dense cores, prior to the formation of a star, may evade detection by conventional methods of probing cores using molecular emission. Under these conditions H$_2$D$^+$ may be the sole viable molecular probe of the innermost regions of star forming cores.

Modelling methanol and hydroxyl masers in star-forming regions

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Class II methanol masers are found in close association with OH main-line masers in many star-forming regions, where both are believed to flag the early stages in the evolution of a massive star. We have studied the formation of masers in methanol and OH under identical model conditions for the first time. Infrared pumping by radiation from warm dust at temperature > 100 K can account for the known maser lines in both molecules, many of which develop simultaneously under a range of conditions. The masers form most readily in cooler gas (< 100 K) of moderately high density ($10^5 - 10^8$ cm^{-3}), though higher gas temperatures and/or lower densities are also compatible with maser action. The agreement between the current model (developed for methanol) and the established OH maser trends is

very encouraging, and we anticipate that further tuning of the model will further improve such agreement.

We find the gas phase molecular abundance to be the key determinant of observable maser activity for both molecules. Sources exhibiting both 6668 MHz methanol and 1665 MHz OH masers have typical flux density ratio of 16; our model suggests that this may be a consequence of maser saturation. We find that the 1665 MHz maser approaches the saturated limit for OH abundances $> 10^{-7.3}$, while the 6668 MHz maser requires a greater methanol abundance $> 10^{-6}$. OH-favoured sources are likely to be less abundant in methanol, while methanol-favoured sources may be less abundant in OH or experiencing warm (> 125 K) dense ($\sim 10^7$ cm^{-3}) conditions. These abundance requirements offer the possibility of tying the appearance of masers to the age of the new-born star via models of gas phase chemical evolution following the evaporation of icy grain mantles.

X-ray emitting young stars in the Orion Nebula

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The Orion Nebula Cluster and the molecular cloud in its vicinity have been observed with the ACIS-I detector on board the *Chandra X-ray Observatory* with 23 hours exposure in two observations. We detect 1075 X-ray sources, most with sub-arcsecond positional accuracy. Ninety-one percent of the sources are spatially associated with known stellar members of the cluster, and an additional 7% are newly identified deeply embedded cloud members. This provides the largest X-ray study of a pre-main sequence stellar population and covers the initial mass function from brown dwarfs up to a 45 M$_\odot$ O star. Source luminosities span 5 orders of magnitude from $\log L_x \simeq 28.0$ to 33.3 erg s^{-1} in the $0.5 - 8$ keV band, plasma energies range from 0.2 to >10 keV, and absorption ranges from $\log N_H < 20.0$ to ~ 23.5 cm^{-2}. Comprehensive tables providing X-ray and stellar characteristics are provided electronically.

We examine here the X-ray properties of Orion young stars as a function of mass; other studies of astrophysical interest will appear in companion papers. Results include: (a) the discovery of rapid variability in the O9.5 31 M$_\odot$ star θ^2A Ori, and several early B stars, inconsistent with the standard model of X-ray production in small shocks distributed throughout the radiatively accelerated wind; (b) support for the hypothesis that intermediate-mass mid-B through A type stars do not themselves produce significant X-ray emission; (c) confirmation that low-mass G- through M-type T Tauri stars exhibit powerful flaring but typically at luminosities considerably below the 'saturation' level; (d) confirmation that the presence or absence of a circumstellar disk has no discernable effect on X-ray emission; (e) evidence that T Tauri plasma temperatures are often very high with $T \geq 100$ MK, even when luminosities are modest and flaring is not evident; and (f) detection of the largest sample of pre-main sequence very low mass objects showing flaring levels similar to those seen in more massive T Tauri stars and a decline in magnetic activity as they evolve into L- and T-type brown dwarfs.

The history of mass dispersal around Herbig Ae/Be stars

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We present a systematic study of the material surrounding intermediate-mass stars. Our sample includes 34 Herbig Ae/Be (HAEBE) stars of different ages and luminosities. This is a quite complete representation of the whole class of HAEBE stars and consequently, our conclusions should have a solid statistical meaning. In addition, we have observed 2 intermediate-mass protostars and included published data on 15 protostellar objects in order to determine the evolution of the circumstellar material in the early stages of stellar evolution. All the HAEBE stars have been classified according with the three Types already defined in Fuente et al. (1998): Type I stars are immersed in a dense clump and have associated bipolar outflows, their ages are ~ 0.1 Myr; Type II stars are still immersed in the molecular cloud though not in a dense clump, their ages are between $\sim$ a few 0.1 to $\sim$ a few Myr; Type III stars have completely dispersed the surrounding material and are located in a cavity of the molecular cloud, their ages are > 1 Myr. Our observations are used to reconstruct the evolution of the circumstellar material around intermediate-mass stars and investigate the mass dispersal mechanisms at the different stages of the stellar evolution. Our results can be summarized as follows: Intermediate-mass stars disperse ≥ 90 % of the mass of the parent clump during the protostellar phase. During this phase, the energetic outflows sweep out the gas and dust forming a biconical cavity while the equatorial material is infalling to feed the circumstellar disk and eventually the protostar. In this way, the density structure of the parent clump keeps well described by a density law $n \propto r^{\beta}$ with $-2 < \beta < -1$ although a large fraction of the mass is dispersed. In $\sim$ a few 0.1 Myr, the star becomes visible and the outflow fades. Small material is dispersed from $\sim$ a few 0.1 to ≥ 1 Myr. Since the outflow declines and the stars are still too cold to generate UV photons, stellar winds are expected to be the only dispersal mechanism at work. In 1 Myr an early-type star (B0-B5) and in ≥ 1 to 10 Myr a late-type star (later than B6) meets the ZAMS. Now the star is hot enough to produce UV photons and starts excavating the molecular cloud. Significant differences exist between early-type and late-type stars at this evolutionary stage. Only early-type stars are able to create large (R>0.08 pc) cavities in the molecular cloud producing a dramatic change in the morphology of the region. This difference is easily understood if photodissociation plays an important role in the mass dispersal around these objects.

Linear Sequences of Starless Cores and Young Stellar Objects in the Eagle Nebula

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We observed heads of two molecular pillars in the Eagle Nebula using the Nobeyama Millimeter Array with a spatial resolution of 3, 5, and 3 arcseconds in the ^{13}CO($J = 1 - 0$) line, C^{18}O($J = 1 - 0$) line and 2.7-mm continuum, respectively. We found 6 ^{13}CO sub-clumps and 4 C^{18}O cores. The ^{13}CO clouds are elongated so as to have a head-tail structure, with the heads orientated towards the O star exciting M16. The elongation is likely to be due to radiation or wind from the O star. The cloud surface appears to be compressed, as indicated by strong ^{13}CO emission at the cloud rim. The shapes of the ^{13}CO clouds are quite similar to those of the dark cloud observed in the near infrared. Three out of the 4 C^{18}O cores are located within one of the ^{13}CO clouds. One of the 3 cores, located near the tip of the ^{13}CO cloud, is associated with a 2.7-mm continuum emission peak and is most likely to be a protostar. It is not associated with a known near infrared source. The other two cores are located further from the O star and are most likely to be starless cores. Thus these C^{18}O cores are aligned in order of age, with more-evolved objects closer to the O star. This linear sequence suggests propagation of star formation activity, i.e., sequential star formation, driven by the O star. A similar sequence of a YSO and a C^{18}O core was found in the other head of molecular pillar.

The Evolution of The Circumstellar Environment of Embedded Young Stars from Observations of Rare Species of Carbon Monoxide

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Studies of the properties of the circumstellar material around young embedded sources can provide important insights in to the relative importance of infall and outflow in clearing the circumstellar environment. In this paper we report one such study of 20 of the most deeply embedded young stars in the Taurus molecular cloud using the J= $1 \rightarrow 0$ J= $2 \rightarrow 1$ and J= $3 \rightarrow 2$ transitions of $C^{18}O$ and $C^{17}O$. The profiles comprise a narrow component, with a line width of ~ 0.7 km s^{-1} plus in many cases a second broader component which contains a similar mass of material. The broad component line width decreases with increasing source age as measured by the source bolometeric temperature, consistent with what would be expected if the broad component traces the interaction between a stellar wind and ambient material. The momentum flux of the broad component emission in the immediate vicinity of the forming star is comparable to that in the spatially extended outflows from these sources and also decreases with increasing source age. Comparison with models of this interaction provide a reasonable match to the behaviour of the broad component with source age.

The derived total column density towards the sources shows a systematic decrease with increasing bolometric temperature and implies a circumstellar mass loss rate that varies from $\sim 10^{-4}$ M$_\odot$yr^{-1} for the youngest sources to $\sim 10^{-8}$ M$_\odot$yr^{-1} for sources in the late Class I phase.

The broad components are sufficiently massive and energetic to clear the circumstellar environment on time scales of $\sim 10^5$ years, and we argue that the broad component of the $C^{18}O$ line profiles is the dense, low velocity inner part of the outflow from the sources and may be the material being directly swept up by the stellar wind. The widths of the broad and narrrow components are correlated indicating that the narrow component material is already being stirred by the stellar wind, even in the youngest sources.

The threaded molecular clumps of Chamaeleon III

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We have mapped large areas in the Chamaeleon III complex of molecular clouds with the SEST in $^{13}CO(J = 1 - 0)$ and in $C^{18}O(J = 1 - 0)$. The stronger CO emission coincides with areas of cold dust emission, which is distributed in long, but thin, wavy filaments. We identify some 40 clumps of enhanced CO emission in these filaments. In the southern part of Cha III the clumps are equidistant along the main zig-zag shaped filament. Here we find two systems of filaments moving at different radial velocities. At least part of the zig-zag patterns visible on optical images may be caused by overlapping filaments. All clumps are small (typically 0.02 - 0.05 pc in radius), and of small mass (typically $0.1 - 0.7$ $M_\odot$, when assuming the 'standard' $C^{18}O/H_2$ column density ratio). Also the average number densities are small, $n(H_2) = 1\,10^4 - 8\,10^4$ cm^{-3}, and the density contrast between clump and interclump gas is only ~ 10. In addition the values of $|E_{pot}|/E_{kin}$ are unusually small, 0.03 - 0.33. These clumps, or rather concentrations, have smaller masses than the condensations so far identified in other molecular clouds. Previously reported clumps of larger masses in Cha III turn out to be composed of assemblies of clumps. There are no signs of star formation in Cha III (unlike Cha I and Cha II), and our results indicate also that such activity is not expected. However, with the velocity dispersion of 0.2 km s^{-1} the clumps would leave the thin filaments on short timescales, and if the clumps as such are not confined by some external force, they would also lose their identity on even shorter timescales. We discuss the possibility that the clumps are confined by electro-magnetic forces, and show that this may work with reasonable

assumptions on the required magnetic field strength. We also discuss the possibility that the clumps are attached to magnetic ropes along the filamentary axis, in which case the clumps could swing back and forth perpendicularly to the axis, like they were threaded on elastic strings.

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On the nature of variations in the T Tauri star WY Arietis (LkHα 264)

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We report optical spectroscopic and photometric results from our long-term study of the T Tauri star WY Arietis (LkHα 264). The data gathered show different types of variability: variations in the continuum level, in the emission line fluxes and line profiles. The timescales associated with these variations appear quite diverse. The correlation found between the variations observed in the veiling and in the continuum flux strongly suggest that an extra continuum source veiling the stellar photospheric spectrum is the cause driving the continuum variability. The present work also unveils the presence of an accretion flow onto the star, as revealed by the O I $\lambda7773$ Å and $\lambda8446$ Å line profiles, which is the first unambiguous model-independent detection of such an event in this star. Our photometric data allowed us to find a period of 3.04 days for this star, somewhat in tune with Fernandez & Eiroa (1996). However, due to the poor time sampling our finding should be taken as tentative. A detailed analysis of the broad and narrow components of the He I line profiles indicates the presence of a hot wind during the November 1993 observation while in October 1999 a wind is only revealed by the blue wing asymmetry of the observed Balmer and CaII infrared triplet line profiles. The correlation between the strength of the hot wind and the amount of flux in the emission lines led also to the conclusion that this type of wind provides a significant contribution to the hydrogen and metal emission lines. We have also witnessed an exceptional activity during one of the nights which may be attributed to an increase in LkHα 264's accretion rate or to a flare-like event. Although it is not possible to clearly distinguish between these possibilities, the available data set points towards variable accretion as being responsible for the observed event.

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Mass Loading by Proplyds of an O-Star Wind

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We present time-dependent, one-dimensional, numerical simulations of the mass loading of the stellar wind from a high-mass star due to embedded proplyds. The simulations are tailored to the O star θ^1 Ori C in the Orion nebula, using realistic mass-loading rates taken from detailed studies of the Orion proplyds. We find significant dynamical effects on the wind due to the mass loading that can be directly compared with observational probes of the radial dependence of the wind pressure.

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Spatial distribution of emission in Unidentified Infrared Bands from Midcourse Space Experiment Survey

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Recently the Midcourse Space Experiment (MSX) has surveyed the Galactic plane in mainly four infrared bands between 6 and 25 μm. Two of these bands cover several Unidentified Infrared emission Bands (UIBs). With the aim of extracting the spatial distribution of the UIB emission on a large scale, a scheme has been developed to model the MSX data with emission in the UIBs alongwith the underlying thermal continuum from the interstellar dust. In order to test this scheme, a sample of five Galactic compact H II regions (Sh-61, Sh-138, Sh-152, Sh-156, Sh-186; Zavagno & Ducci 2001) for which imaging study in some individual UIBs is available from ISOCAM measurements, has been studied. The results of this comparative study on small angular scale are as follows : (i) the morphological details extracted from our scheme agree very well with those from the superior ISOCAM measurements; (ii) the integrated strength of UIBs extracted from the MSX database correlates extremely well with the sum of the strengths of individual UIBs measured from ISOCAM. This tight correlation is very encouraging and promises the potential of MSX database for study of large scale spatial distribution of UIB emission (and the carriers of UIBs) in the entire Galactic plane.

Understanding the nature of protostellar jets through near infrared spectroscopy: the key role of the J band proven on HH43

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Spectroscopy in the J-band (even at low resolution, R $\leq 10^3$) is a mode commonly available in most of the near IR spectrographs but rarely exploited in star formation studies. We show how it is a crucial tool to trace the physics (temperature, density, excitation mechanisms) of protostellar jets and Herbig-Haro (HH) objects. In this framework the spectrum of HH43 is revisited as both a clear demonstration of our statement and a case of slow J-ump shock excitation.

Photoevaporation of Clumps in Photodissociation Regions

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We present the results of an investigation of the effects of Far Ultraviolet (FUV) radiation ($6.0eV < h\nu < 13.6eV$) from hot early type OB stars on clumps in star-forming molecular clouds. Clumps in FUV-illuminated regions (or photodissociation regions or PDRs) undergo external heating and photodissociation as they are exposed to the FUV field, resulting in a loss of cold, molecular clump mass as it is converted to warm atomic gas. The heating, if rapid, creates strong photoevaporative mass flows off the clump surfaces, and drives shocks into the clumps, compressing them to high densities. The clumps lose mass on relatively short timescales. The evolution of an individual clump is found to be sensitive to three dimensionless parameters: η_{c0}, the ratio of the initial column density of the clump to the column $N_0 \sim 10^{21}$ cm^{-2} of a warm FUV-heated surface region; ν, the ratio of the sound speed in the heated surface to that in the cold clump material; and t_{FUV}/t_c, the ratio of the "turn-on time" t_{FUV} of the heating flux on a clump to its initial sound crossing-time t_c. The evolution also depends on whether a confining interclump medium exists, or whether the interclump region has negligible pressure, as is the case for turbulence-generated clumps. In this paper, we use spherical 1-D numerical hydrodynamic models as well as approximate analytical models to study the dependence of clump photoevaporation on the physical parameters of the clump, and to derive the dynamical evolution, mass loss

rates and photoevaporative timescales of a clump for a variety of astrophysical situations. Turbulent clumps evolve so that their column densities are equal to a critical value determined by the local FUV field, and typically have short photoevaporation timescales, $\sim 10^{4-5}$ years for a 1 M$_\odot$ clump in a typical star-forming region ($\eta_{c0} = 10, \nu = 10$). Clumps with insufficient magnetic pressure support, and in strong FUV fields may be driven to collapse by the compressional effect of converging shock waves. We also estimate the rocket effect on photoevaporating clumps and find that it is significant only for the smallest clumps, with sizes much less than the extent of the PDR itself. Clumps that are confined by an interclump medium may either get completely photoevaporated, or may preserve a shielded core with a warm, dissociated, protective shell that absorbs the incident FUV flux. We compare our results with observations of some well-studied PDRs: the Orion Bar, M17SW, NGC 2023 and the Rosette Nebula. The data are consistent with both interpretations of clump origin, turbulence and pressure confinement, with a slight indication for favouring the turbulent model for clumps over pressure-confined clumps.

Multiple Flow Interactions in a Proplyd Binary System
I. The Interproplyd Shell

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The Orion nebula proplyd 168–326 (LV 1) consists of a pair of photoevaporation flows, one from the circumstellar disk of each member of a protostellar binary system. The two flows collide at mildly supersonic velocities, producing a dense interproplyd shell bounded by two weak shocks, while further interactions occur between the individual photoevaporation flows and the stellar wind from the ionizing star θ^1 Ori C. I show how observations of the interproplyd shell allow the geometry of the binary system to be usefully constrained and investigate to what extent the weak shocks may directly contribute to the observed shell emission at optical and radio wavelengths.

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A Global Jet/Circulation Model for Young Stars

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Powerful, highly collimated jets, surrounded by bipolar molecular outflows, are commonly observed near Young Stellar Objects (YSOs). In the usual theoretical picture of star formation, a jet is ejected from a magnetized accretion disk, with a molecular outflow being driven either by the jet or by a wider wind coming from the disk. Here, we propose an alternative global model for the flows surrounding YSOs. In addition to a central accretion-ejection engine driving the jet, the molecular outflow is powered by the infalling matter and follows a circulation pattern around the central object without necessarily being entrained by a jet. It is shown that the model produces a heated pressure-driven outflow with magneto-centrifugal acceleration and collimation. We report solutions for the three different parts of this self-similar model, i.e. the jet, the infalling envelope and the circulating matter that eventually forms the molecular outflow. This new picture of the accretion/outflow phase provides a possible explanation for several observed properties of YSO outflows. The most relevant ones are the presence of high mass molecular outflows around massive protostars, and a realistic fraction (typically 0.1) of the accretion flow that goes into the jet.

Large proper motions in the young low–mass protostellar system IRAS 16293–2422

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We compare high angular resolution VLA 3.6 cm continuum observations of the protostellar system IRAS 16293–2422 obtained in 1989 and 1994, and show that the positions of the three VLA sources in IRAS 16293–2422 have changed significantly between the two epochs. The corresponding angular displacements are much larger than the parallax of those sources, and imply transverse velocities (10–30 km s^{-1}) well above the Keplerian rotation speeds expected for those low–mass sources. The proper motions of two of the components appear to be very similar to one another, and to the proper motions of pre–main sequence stars in the same direction. We argue that they correspond to the overall proper motion of the small cloud (L1689N) harboring IRAS 16293–2422. The displacement of the third source, however, is larger and in a different direction. That component has previously been argued to be a shock between a partly ionized wind, and the ambient medium, so some fast motions are not unexpected. It is somewhat puzzling, however, that the direction of the motion does not coincide with the direction of any of the known outflows powered by IRAS 16293–2422.

Doubly deuterated formaldehyde in star–forming regions : An observational approach

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We present the results of a search for the doubly deuterated form of formaldehyde (D_2CO) in a large sample of objects associated to star–formation. D_2CO was detected in nearly 20 low–mass protostars, a success rate of 100%, with $[D_2CO]/[H_2CO]$ abundance ratios of 2–40%. On the other hand, no detection was obtained towards more massive protostars (where $[D_2CO]/[H_2CO] < 0.5\%$) nor towards the shocks along the molecular outflows powered by protostar (where $[D_2CO]/[H_2CO] < 0.5$–1%). The results reported here multiply the number of D_2CO detections by a factor of 6.

Since low temperatures and high densities are needed to obtain high levels of multiple deuteration, the D_2CO detected towards low–mass protostars is most likely currently desorbed from dust grain mantles where it has accumulated and/or formed during the earlier and colder pre–stellar stage. The lack of detection towards molecular outflows is naturally explained in this scheme since the high velocity gas there is mostly previously ambient material, that never went through the cold phase required to attain high deuteration levels. The lack of detection towards higher mass protostars indicates that the chemistry in low–mass protostars is significantly different from that in higher mass objects, and that much caution should be used when generalizing chemical results obtained in high–mass sources to low–mass objects.

Circumstellar disks around Herbig Ae/Be stars: polarization, outflows and binary orbits

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The geometrical relationship between the distribution of circumstellar matter, observed optical linear polarization, outflows and binary orbital plane in Herbig Ae/Be stars is investigated. Optical linear polarization measurements carried out for a number of Herbig Ae/Be stars that are either known to be in binary systems and/or have bipolar jets are presented in this paper. Available information on the position angles of polarization, outflows and binary companions for Herbig Ae/Be stars is compiled and analysed for any possible correlations. In ≈ 85% of the sources the outflow position angle is within 30° of being parallel or perpendicular to the polarization position angle. In ≈ 81% of the sources the binary position angle is within 30° of being parallel or perpendicular to the polarization position angle. Out of 15 sources with bipolar outflows, 10 sources have the binary position angle within 30° of being perpendicular to the outflow position angle. These results favour those binary formation mechanisms in which the binary components and the disks around individual stars or circumbinary disks are coplanar.

Non-emission line young stars of intermediate mass

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We present optical spectra of four intermediate mass candidate young stellar objects that have often been classified as Herbig Ae/Be stars. Typical Herbig Ae/Be emission features are not present in the spectra of these stars. Three of them, HD 36917, HD 36982 and HD 37062 are members of the young Orion Nebula Cluster (ONC). This association constrains their ages to be ≤ 1 Myr. The lack of appreciable near infrared excess in them suggests the absence of hot dust close to the central star. But they do possess significant amounts of cold and extended dust component as revealed by the large excess emission observed at far infrared wavelengths. Fractional infrared luminosity ($L_{ir}/L_\star$) and the dust masses computed from IRAS fluxes are systematically lower than that found for Herbig Ae/Be stars but higher than those for Vega-like stars. These stars may then represent the youngest examples of Vega phenomenon known so far. In contrast, the other star in our sample, HD 58647, is more likely to be a classical Be star as evident from the low $L_{ir}/L_\star$, scarcity of circumstellar dust, low polarization, presence of Hα emission and near infrared excess and far infrared spectral energy distribution consistent with free-free emission similar to other well known classical Be stars.

Simulation-Based Investigation of a Model for the Interaction Between Stellar Magnetospheres and Circumstellar Accretion Disks

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We examine, parametrically, the interaction between the magnetosphere of a rotating, young stellar object (YSO) and a circumstellar accretion disk using 2.5-D (cylindrically symmetric) numerical magnetoydrodynamic simulations. The interaction drives a collimated outflow, and we find that the jet formation mechanism is robust. For variations in initial disk density of a factor of 16, variations of stellar dipole strength of a factor of 4, and for various initial conditions

with respect to the disk truncation radius and the existence of a disk field, outflows with similar morphologies were consistently produced. Secondly, the system is self-regulating, where the outflow properties depend relatively weakly on the parameters above. The large scale magnetic field structure rapidly evolves to a configuration that removes angular momentum from the disk at a rate that depends most strongly on the field and weakly on the rotation rate of the foot-points of the field in the disk and the mass outflow rate. Third, the simulated jets are episodic, with the timescale of jet outbursts identical to the timescale of magnetically induced oscillations of the inner edge of the disk. To better understand the physics controlling these disk oscillations, we present a semi-analytical model and confirm that the oscillation period is set by the spin down rate of the disk inner edge. Finally, our simulations offer strong evidence that it is indeed the interaction of the stellar magnetosphere with the disk, rather than some primordial field in the disk itself, that is responsible for the formation of jets from these systems.

Massive star formation in 100,000 years from turbulent and pressurized molecular clouds

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Massive stars (with mass $m_* \gtrsim 8M_\odot$) are fundamental to the evolution of galaxies, because they produce heavy elements, inject energy into the interstellar medium, and possibly regulate the star formation rate. The individual star formation time, t_{*f}, determines the accretion rate of the star; the value of the former quantity is currently uncertain by many orders of magnitude, leading to other astrophysical questions. For example, the variation of t_{*f} with stellar mass dictates whether massive stars can form simultaneously with low-mass stars in clusters. Here we show that t_{*f} is determined by conditions in the star's natal cloud, and is typically $\sim 10^5$yr. The corresponding mass accretion rate depends on the pressure within the cloud—which we relate to the gas surface density—and on both the instantaneous and final stellar masses. Characteristic accretion rates are sufficient to overcome radiation pressure from $\sim 100M_\odot$ protostars, while simultaneously driving intense bipolar gas outflows. The weak dependence of t_{*f} on the final mass of the star allows high- and low-mass star formation to occur nearly simultaneously in clusters.

The Luminosity & Mass Function of the Trapezium Cluster:
From B stars to the Deuterium Burning Limit

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We use the results of a new, multi-epoch, multi-wavelength, near-infrared census of the Trapezium Cluster in Orion to construct and to analyze the structure of its infrared (K band) luminosity function. Specifically, we employ an improved set of model luminosity functions to derive this cluster's underlying Initial Mass Function (IMF) across the entire range of mass from OB stars to sub-stellar objects down to near the deuterium burning limit. We derive an IMF for the Trapezium Cluster that rises with decreasing mass, having a Salpeter-like IMF slope until near $\sim 0.6M_\odot$ where the IMF flattens and forms a broad peak extending to the hydrogen burning limit, below which the IMF declines into the sub-stellar regime. Independent of the details, we find that sub-stellar objects account for no more than $\sim 22\%$ of the total number of likely cluster members. Further, the sub-stellar Trapezium IMF breaks from a steady power-law decline and forms a significant secondary peak at the lowest masses (10-20 times the mass of Jupiter). This secondary peak may contain as many as $\sim 30\%$ of the sub-stellar objects in the cluster. Below this sub-stellar IMF peak, our KLF modeling requires a subsequent sharp decline toward the planetary mass regime. Lastly, we investigate

the robustness of pre-main sequence luminosity evolution as predicted by current evolutionary models, and we discuss possible origins for the IMF of brown dwarfs.

Mechanism of Magnetic Flux Loss in Molecular Clouds

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We investigate the detailed processes working in the drift of magnetic fields in molecular clouds. To the frictional force, whereby the magnetic force is transmitted to neutral molecules, ions contribute more than half only at cloud densities $n_{\rm H} \lesssim 10^4\,{\rm cm}^{-3}$, and charged grains contribute more than about 90% at $n_{\rm H} \gtrsim 10^6\,{\rm cm}^{-3}$. Thus grains play a decisive role in the process of magnetic flux loss. Approximating the flux loss time t_B by a power law $t_B \propto B^{-\gamma}$, where B is the mean field strength in the cloud, we find $\gamma \approx 2$, characteristic to ambipolar diffusion, only at $n_{\rm H} \lesssim 10^7\,{\rm cm}^{-3}$ where ions and smallest grains are pretty well frozen to magnetic fields. At $n_{\rm H} > 10^7\,{\rm cm}^{-3}$, γ decreases steeply with $n_{\rm H}$, and finally at $n_{\rm H} \approx n_{\rm dec} \approx$ a few $\times 10^{11}\,{\rm cm}^{-3}$, where magnetic fields effectively decouple from the gas, $\gamma \ll 1$ is attained, reminiscent of Ohmic dissipation, though flux loss occurs about 10 times faster than by pure Ohmic dissipation. Because even ions are not very well frozen at $n_{\rm H} > 10^7\,{\rm cm}^{-3}$, ions and grains drift slower than magnetic fields. This insufficient freezing makes t_B more and more insensitive to B as $n_{\rm H}$ increases. Ohmic dissipation is dominant only at $n_{\rm H} \gtrsim 1 \times 10^{12}\,{\rm cm}^{-3}$. While ions and electrons drift in the direction of magnetic force at all densities, grains of opposite charges drift in opposite directions at high densities, where grains are major contributors to the frictional force. Although magnetic flux loss occurs significantly faster than by Ohmic dissipation even at very high densities as $n_{\rm H} \approx n_{\rm dec}$, the process going on at high densities is quite different from ambipolar diffusion in which particles of opposite charges are supposed to drift as one unit.

Molecular tracers of photo-evaporating disks around young stars

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Disks around massive young stellar objects, and disks around low-mass stars irradiated by nearby OB associations, are eroded by photo-evaporation. In the latter case, this erosion may be an important factor in planet formation. As Johnstone et al. (1998) have shown, photo-evaporating material is gravitationally retained within a critical radius from the star, and constitutes an envelope similar to a Photon-Dominated Region (PDR) that normally arises at the edge of a molecular cloud irradiated by a massive star. We explore the chemistry of such a PDR/disk system to examine the contribution that it may make to the molecular species that may be observed. The model is in two phases; firstly, a collapse from low density to a high density appropriate for a disk; and, secondly, a 2D calculation of the irradiation of disk material by the radiation field of the central massive star or nearby OB association. The model follows the chemistry self-consistently through both phases. We compute the column densities of species through the PDR/disk system, averaged over the disk. We validate our model by comparing predicted averaged molecular column densities with those of several species detected in the disk around the 10 solar mass star GL 2591, currently the sole example known of this kind of object. Results are in good agreement for a model in which the outer part of the PDR is hot while the inner part is cool, and in which the local ionization rate is comparable with that caused by cosmic rays in the local interstellar medium. We show that in addition to the four detected species, there should be many others also detectable in this system, including HCN, NH_3 and CS. Similar conclusions should apply to others disks around

massive stars. Disks around low-mass stars are much more common; our models show that when irradiated by a nearby OB association such disks with their attendant PDRs also generate a rich chemistry. No detections of molecules in such objects have yet been reported. However, the models suggest that averaged molecular column densities should be comparable to those detected in disks around massive stars (see references listed in Table 4) for molecules in GL 2591). Potential tracers of irradiated disks around low-mass stars include OH, CH_3 and C_2H.

We note that the detection in a disk of PDR-type chemistry is a clear signature that the disk is undergoing erosion. Its duration is therefore limited, with consequences for planet formation.

Evolution in the far infrared spectra of low-mass young embedded sources

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The far infrared spectra (45–197μm) of 28 low luminosity young embedded objects have been studied in order to search for possible evolutive trends in the observed spectral features. The low resolution spectra from 45 to 197μm of 17 Class 0 and 11 Class I sources taken with the Long Wavelength Spectrometer (LWS) on-board the *Infrared Space Observatory* have been used for this analysis. The most prominent features presented by these spectra are the [O I]63μm and 145μm fine structure lines, and pure rotational lines from the abundant molecules CO, H_2O and OH. Clear differences are however found between the spectra of the two classes of objects. Water lines, which are prominent in the spectra of Class 0 sources, are not observed in Class I objects, with an upper limit $\leq 10^{-5}$ on the H_2O abundance. Furthermore, the total cooling due to molecular emission in Class 0 sources is on average significantly larger than in Class I sources, while the cooling due to atomic oxygen is fairly constant among the two classes of objects. Finally, the total gas cooling as traced by the far infrared lines (L_{FIR}), results to be correlated with the bolometric luminosity for the Class 0 sample of sources, with a L_{FIR}/L_{bol} ratio ($\sim 10^{-2}$) of about an order of magnitude larger than in Class I sources. We suggest that most of the observed emission lines originates from shocks at the base and along the source outflows. In such a case these results can be interpreted in terms of a change in the modality of the interaction between the protostellar jet and the circumstellar environment. During the Class 0 phase the impact of energetic flows with the dense ambient medium gives rise to a strong component of non-dissociative C-type shock, while during the Class I phase such impact produces less energetic shocks with an enhanced dissociative J-type component. Finally, the low H_2O abundance found in Class I sources can be explained by the action of the progressively less shielded interstellar UV field.

Surface hydrogenation in diffuse and translucent interstellar clouds

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We investigate the effects of grain-surface hydrogenation reactions on gas phase chemical models of diffuse and translucent clouds in the interstellar medium. Models in which gas phase species freeze out on to dust without release do not match observed column densities well. Expanding on previous work we extend our models to include the release of C, N, O, S and CO following hydrogenation on the grain surface. The results show that such mechanisms do improve the ability of chemical models to reproduce observed abundances, not only through the release of otherwise frozen-out species but also because of the additional hydrogenating reactions. For example, the predicted column densities of NH in diffuse clouds and H_2S and NH_3 in translucent clouds match observations better in models with grain-surface hydrogenation.

The Early Angular Momentum History of Low Mass Stars: Evidence for a Regulation Mechanism

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We examine the early angular momentum history of stars in young clusters via 197 photometric periods in fields flanking the Orion Nebula Cluster (ONC), 81 photometric periods in NGC 2264, and 202 measurements of $v \sin i$ in the ONC itself. We show that PMS stars spanning an age range from 0.1 to 3 Myr do not appear to conserve stellar angular momentum as they evolve down their convective tracks, but instead preserve the same range of periods even though they have contracted by about a factor of three. This result seems to require a mechanism that regulates the angular velocities of young stars. We discuss several candidate mechanisms. The most plausible appears to be disk-locking, though most of our stars do not have $I_C - K_s$ excesses suggestive of disks. However, a decisive test of this hypothesis requires a more sensitive diagnostic than the $I_C - K_s$ excesses used here.

Primordial substructure in the Orion Nebula Cluster

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We use numerical N-body simulations of the Orion Nebula Cluster (ONC) to investigate the possibility of substructure in its formation. There is no substructure apparent in the ONC today. However, unless there was a remarkable degree of homogeneity in the molecular cloud from which it formed, it seems unlikely that this would have been true of the cluster in its earliest phase. More plausibly, the early structure of the cluster would have consisted of groups or clumps of subclusters, following the structure of the cloud itself. We have explored the extent to which such subclusters could subsequently have merged, and find that the age of the cluster is a critical factor. The most inhomogeneous initial conditions, comprising a small number of subclusters with many members, are ruled out by an age of 2 Myr or less. There is considerable freedom in the other direction, however, which suggests that fragmentation in the original cloud is more likely to have been on the scale of small clumps, each producing less than a hundred stars. These initial subclusters could have been very dense—perhaps two or three orders of magnitude more dense than the core of the ONC today.

Tracing the Mass during Low-Mass Star Formation. III. Models of the Submillimeter Dust Continuum Emission from Class 0 Protostars

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Seven Class 0 sources mapped with SCUBA at 850 and 450 μm are modeled using a one dimensional radiative transfer code. The modeling takes into account heating from an internal protostar, heating from the ISRF, realistic beam effects, and chopping to model the normalized intensity profile and spectral energy distribution. Power law density

models, $n(r) \propto r^{-p}$, fit all of the sources; best fit values are mostly $p = 1.8 \pm 0.1$, but two sources with aspherical emission contours have lower values ($p \sim 1.1$). Including all sources, $mean p = 1.63 \pm 0.33$. Based on studies of the sensitivity of the best-fit p to variations in other input parameters, uncertainties in p for an envelope model are $\Delta p = \pm 0.2$. If an unresolved source (e.g., a disk) contributes 70% of the flux at the peak, p is lowered in this extreme case and $\Delta p = ^{+0.2}_{-0.6}$. The models allow a determination of the internal luminosity ($mean L_{int} = 4.0$ L$_\odot$) of the central protostar as well as a characteristic dust temperature for mass determination ($mean T_{iso} = 13.8 \pm 2.4$ K). We find that heating from the ISRF strongly affects the shape of the dust temperature profile and the normalized intensity profile, but does not contribute strongly to the overall bolometric luminosity of Class 0 sources. There is little evidence for variation in the dust opacity as a function of distance from the central source. The data are well-fitted by dust opacities for coagulated dust grains with ice mantles (Ossenkopf & Henning 1994). The density profile from an inside-out collapse model (Shu 1977) does not fit the data well, unless the infall radius is set so small as to make the density nearly a power-law.

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Dynamical relaxation and the orbits of low–mass extrasolar planets

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We consider the evolution of a system containing a population of massive planets formed rapidly through a fragmentation process occurring on a scale on the order of 100 au and a lower mass planet that assembles in a disc on a much longer timescale. During the formation phase, the inner planet is kept on a circular orbit due to tidal interaction with the disc, while the outer planets undergo dynamical relaxation. Interaction with the massive planets left in the system after the inner planet forms may increase the eccentricity of the inner orbit to high values, producing systems similar to those observed.

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The role of damped Alfvén waves on magnetospheric accretion models of young stars

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We examine the role of Alfvén wave damping in heating the plasma in the magnetic funnels of magnetospheric accretion models of young stars. We study four different damping mechanisms of the Alfvén waves: nonlinear, turbulent, viscous-resistive and collisional. Two different possible origins for the Alfvén waves are discussed: 1) Alfvén waves generated at the surface of the star by the shock produced by the infalling matter; and 2) Alfvén waves generated locally in the funnel by the Kelvin-Helmholtz instability. We find that, in general, the damping lengths are smaller than the tube length. Since thermal conduction in the tube is not efficient, Alfvén waves generated only at the star's surface cannot heat the tube to the temperatures necessary to fit the observations. Only for very low frequency Alfvén waves $\sim 10^{-5}$ the ion cyclotron frequency, is the viscous-resistive damping length greater than the tube length. In this case, the Alfvén waves produced at the surface of the star are able to heat the whole tube. Otherwise, local production of Alfvén waves is required to explain the observations. The turbulence level is calculated for different frequencies for optically thin and thick media. We find that turbulent velocities varies greatly for different damping mechanisms, reaching ~ 100 km s^{-1} for the collisional damping of small frequency waves.

Scattering and Absorption by Aligned Grains in Circumstellar Environments

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We present radiative transfer calculations showing the polarization effects of scattering and absorption by aligned grains. The grain model consists of a size distribution of oblate or spinning prolate particles with varying degrees of alignment. To develop an understanding of the radiative transfer effects, we begin with the simple case of a spherical envelope illuminated by a central source with constant grain alignment axis throughout the envelope. Non-aligned grains produce no net polarization in such envelopes, while aligned grains produce substantial linear and circular polarization. The linear polarization results from the competing effects of differential extinction and scattering. The polarization varies strongly with optical depth, with scattering dominating at low optical depth and differential extinction dominating at high optical depth. The net, or integrated, circular polarization from the envelopes is zero; however the circular polarization across the resolved nebula is large, reaching $\pm 50\%$ in the "diagonal" regions of the nebula. Next, we calculate axisymmetric models of protostellar envelopes, again with the simplifying case of constant grain alignment axis throughout the envelope. The polarization maps show differences from the case of non-aligned grains, especially in the disk midplane, where differential extinction of even the scattered light causes the polarization vectors to align perpendicular to the diskplane, in contrast to many observations. This suggests that either grains are not aligned in protostellar envelopes, or that the magnetic field (the presumed alignment mechanism) is not aligned along the disk rotational axis throughout the envelope and disk. A definitive test of grain alignment could come from resolved circular polarization maps of protostars. Aligned grains produce large values of circular polarization across the cloud, up to $\pm 25 - 40\%$ in the models presented here, whereas non-aligned grains produce maximum polarizations of $< 1\%$. In objects with aligned grains, analysis of linear and circular polarization maps can probe magnetic geometries.

Structure in the Dusty Debris around Vega

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We present images of the Vega system obtained with the IRAM Plateau de Bure interferometer at 1.3 millimeters wavelength with sub-mJy sensitivity and $\sim 2\rlap{.}''5$ resolution (about 20 AU). These observations clearly detect the stellar photosphere and two dust emission peaks offset from the star by $9\rlap{.}''5$ and $8\rlap{.}''0$ to the northeast and southwest, respectively. These offset emission peaks are consistent with the barely resolved structure visible in previous submillimeter images, and they account for a large fraction of the dust emission. The presence of two dust concentrations at the observed locations is plausibly explained by the dynamical influence of an unseen planet of a few Jupiter masses in a highly eccentric orbit that traps dust in principal mean motion resonances.

Collisional Processes in Extrasolar Planetesimal Disks — Dust Clumps in Fomalhaut's Debris Disk

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This paper presents a model for the outcome of collisions between planetesimals in a debris disk and assesses the impact of collisional processes on the structure and size distribution of the disk. The model is presented by its application to Fomalhaut's collisionally replenished dust disk; a recent 450 μm image of this disk shows a clump embedded within it with a flux ~ 5 per cent of the total. The following conclusions are drawn: **(i)** SED modelling is consistent with Fomalhaut's disk having a collisional cascade size distribution extending from bodies 0.2 m in diameter (the largest that contribute to the 850 μm flux) down to 7 μm-sized dust (smaller grains are blown out of the system by radiation pressure). **(ii)** Collisional lifetime arguments imply that the collisional cascade starts with planetesimals 1.5–4 km in diameter, and so has a mass of 20–30 $M_\oplus$. Any larger bodies must be predominantly primordial. **(iii)** Constraints on the timescale for the ignition of the collisional cascade from planet formation models are consistent with these primordial planetesimals having the same distribution as the cascade extending up to 1000 km, resulting in a disk mass of 5–10 times the minimum mass solar nebula. **(iv)** The debris disk is expected to be intrinsically clumpy, since planetesimal collisions result in dust clumps that can last up to 700 orbital periods. The intrinsic clumpiness of Fomalhaut's disk is below current detection limits, but could be detectable by future observatories such as the *ALMA*, and could provide the only way of determining this primordial planetesimal population. Also, we note that such intrinsic clumpiness in an exozodiacal cloud-like disk could present a confusion limit when trying to detect terrestrial planets. **(v)** The observed clump could have originated in a collision between two runaway planetesimals, both larger than 1400 km diameter. It appears unlikely that we should witness such an event unless both the formation of these runaways and the ignition of the collisional cascade occurred relatively recently (within the last ~ 10 Myr), however this is a topic which would benefit from further exploration using planet formation and collisional models. **(vi)** Another explanation for Fomalhaut's clump is that ~ 5 per cent of the planetesimals in the ring were trapped in 1:2 resonance with a planet orbiting at 80 AU when it migrated out due to the clearing of a residual planetesimal disk. The motion on the sky of such a clump would be 0.2 arcsec/year, and it would be more prominent at shorter wavelengths.

Dissertation Abstracts

Early stages of massive star formation

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The formation processes of high-mass stars are not well understood, and the basic question can be phrased as: *Do massive stars form similarly to low-mass stars, but with enhanced accretion rates, or are different processes taking place, e.g., the coalescence and merging of intermediate-mass protostars in the very center of star-forming clusters?* This thesis investigates the earliest known stages of massive star formation and studies many characteristic parameters to set constraints on the associated physical processes. The analysis and results of my work strongly support the accretion hypothesis and may be summarized as follows: *Massive stars can form via accretion processes that are qualitatively similar and quantitatively enhanced compared to the low-mass case. Coalescence of protostars may occur in some sources, but our data indicate that merging of protostars is not the dominating process for high-mass star formation.*

Because the inner few AU of a star-forming cluster, where the accretion and/or coalescence processes take place, are difficult to resolve with current observational techniques at typical source distances of several kpc, indirect evidence has to be found to answer the initial question. A sample of 69 high-mass protostellar candidates was selected and studied first statistically from the cm and mm regime to near-infrared wavelengths. The analysis revealed that the chosen sample selection criteria very effectively selected a large number of luminous and massive sources at very early evolutionary stages prior to forming a significant ultracompact HII region. Most likely, these sources produce a large fraction of their luminosity by accretion. A detailed analysis of the intensity and density distributions of the sample from 1.2 mm dust continuum emission maps with $11''$ spatial resolution shows that the single-dish radial profiles are not well fitted by single power-law distributions, but that they steepen towards the outside and flatten towards the center. While we interpret the steepening to the outside as a signature of the finite sizes of the star-forming cores, the inner flattening indicates fragmentation of the massive cores into a number of sub-sources. The latter is also observed in high-resolution interferometric data of some of the regions. Additionally, the inner power-law density distributions do not show strong deviations from density distributions of low-mass star-forming cores, which indicates that the initial conditions of low- and high-mass star formation are not very different.

As massive molecular outflows on large scales provide insights into the star formation process at the center of the regions, we mapped the outflows of a sub-sample in the CO $2 \rightarrow 1$ line. The data, observed at higher spatial resolution ($11''$) than previous studies, reveal that massive bipolar and collimated outflows are as ubiquitous phenomena in high-mass star-forming regions as is also true for their low-mass counterparts. Such collimated outflows are most likely produced by star–disk interactions, and hence, massive stars should have disks as well. The observations presented in this thesis reveal accretion rate estimates in the high-mass regime around 10^{-4} M$_\odot$yr^{-1}, rising as high as 10^{-3} M$_\odot$yr^{-1}. Such accretion rates should be sufficiently high to overcome the radiative pressure of the central protostar, and accretion can continue to form massive stars. Additionally, we find that the accretion rate of the mostmassive object in a core scales roughly linearly with the core mass. Furthermore, a high-resolution interferometric case study of one of our sample sources shows that its outflow, which was already known from single-dish observations, actually splits up into at least three bipolar outflows. One of this outflows is the most collimated massive outflow ever observed in molecular gas. These results give strong support to the hypothesis that massive stars form in analogous fashion to low-mass stars; they merely differ in having higher accretion rates, core masses, luminosities and outflow masses.

A study of CH$_3$OH and H$_2$O masers confirms that both are good signposts of massive star formation in very early evolutionary stages. Furthermore, the data suggest that CH$_3$OH and H$_2$O masers need a similar environment (dense and warm molecular gas), but that, due to the different excitation processes (radiative pumping for CH$_3$OH and collisional pumping for H$_2$O), no spatial correlation exists. Kinematic maser features are shown to be not conclusive

in many cases.

Furthermore, high-energy processes were investigated by X-ray observations with the new satellite telescope CHAN-DRA, and a number of point sources in the hard X-ray band are detected. A comparison with infrared and mm data shows that the X-ray emission does not stem from the most deeply embedded and likely most massive central object, but from embedded nearby sources, some of them very likely intermediate-mass Herbig Ae/Be stars or precursors of them. The data are not sensitive enough to conclude whether the central object is simply not an X-ray source, or whether its emission from a central object is absorbed by the high gas column densities in the surrounding envelope. These X-ray observations mark the beginning of a new field of research, namely the understanding of the production mechanisms of high-energy photons emitted in the X-ray regime at early evolutionary stages of intermediate- and high-mass star formation.

Reprint available at: http://www.mpifr-bonn.mpg.de/staff/beuther

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