The Star Formation Newsletter

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The Star Formation Newsletter is a vehicle for fast distribution of information of interest for astronomers working on star and planet formation and molecular clouds. You can submit material for the following sections: Abstracts of recently accepted papers (only for papers sent to refereed journals), Abstracts of recently accepted major reviews (not standard conference contributions), Dissertation Abstracts (presenting abstracts of new Ph.D dissertations), Meetings (announcing meetings broadly of interest to the star and planet formation and early solar system community), New Jobs (advertising jobs specifically aimed towards persons within the areas of the Newsletter), and Short Announcements (where you can inform or request information from the community). Additionally, the Newsletter brings short overview articles on objects of special interest, physical processes or theoretical results, the early solar system, as well as occasional interviews.

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Cover Picture
Herschel 36 (the bright star in the center of the image) is here shown in an image from HST. The star is a spectroscopic triple system (O7.5V+O9V+B0.5V) which illuminates and ionizes the famous Hourglass Nebula at the center of M8.

Image courtesy NASA, ESA, J. Trauger (Jet Propulsion Laboratory)

Submitting your abstracts

Latex macros for submitting abstracts and dissertation abstracts (by e-mail to reipurth@ifa.hawaii.edu) are appended to each Call for Abstracts. You can also submit via the Newsletter web interface at http://www2.ifa.hawaii.edu/star-formation/index.cfm
Q: You have spent a lifetime studying molecular clouds, in our Galaxy and in nearby galaxies. How did this interest originate?

A: It started in graduate school in 1976. Pat Thaddeus, my advisor, had just built a 1.2 m millimeter-wave telescope on the roof of the physics building at Columbia, and each of his graduate students was given a six hour LST range to map the CO emission from a particular region of the sky. I chose the slot that included Orion, even though the Orion GMCs had already been mapped. I turned my attention to the Rosette Nebula, which had been looked at by one of the other students who found nothing but a few weak lines toward the center of the HII region. I was convinced that the nebula had to have come from something more substantial, so I started a systematic search by doing a 10x10 map, and for a day nothing turned up. By the time I got to point number 98 of the map, I started to get a strong signal, and by the time I got to point number 100, the signal was booming! It became clear that there was in fact a big GMC associated with the Rosette Nebula that was similar in size to the Orion GMC, but lies off to one side of the nebula; the HII region and the molecular cloud complex are transverse to the line of sight. Nevertheless, the HII region could be seen to be clearly interacting with the molecular cloud. I spent the next six days mapping out the GMC. Knowing its distance from the photometry of the O stars, I could get an estimate for the size and mass of the cloud. To this day, I always sneak in a slide of the Rosette nebula when I give a talk on GMCs. Strongly influenced by Adriaan Blaauw’s 1964 Annual Review article on sequential star formation in OB associations, I started a program mapping the molecular clouds connected to the OB associations in the direction of the Galactic anticenter for my thesis. In order to get higher resolution I observed these clouds at the 5m millimeter-wave telescope at McDonald observatory. Coming off the telescope one time, I met Charlie Lada and Bruce Elmegreen who asked what I planned to do for a thesis. I told them that I wanted to investigate Blauuw’s ideas and that perhaps the HII regions drive shocks into the molecular clouds compressing the clouds and ultimately forming new stars. However, Charlie and Bruce were already working on their seminal paper on the mechanism for sequential star formation and my vague thoughts on the matter nevertheless provided an impetus for them to finish quickly. Later that year, Charlie called to tell me that there was going to be a meeting on Giant Molecular Clouds in Wales that summer (1977), the first meeting on that subject, and that I should go. I rounded up some financial support for the trip and at the meeting wound up giving the review talk that Thaddeus was supposed to give. Gathering together the work of Pat’s group, I recognized that the GMCs we were mapping all had similar properties and although I didn’t realize it at the time, I presented what turned out to be the first survey of GMCs anywhere. Since it was the second talk of the meeting, every subsequent paper referred to it and the attention was a dizzying experience for a fresh-faced graduate student. As a result, I was hooked.

Q: In 1980 you and Frank Shu published an influential paper showing that giant molecular clouds generally have ages of less than 30 million years. What was the context of this result?

A: At the end of the 1970s, a few people were speculating about the ages of GMCs. There was the camp that argued that GMCs were old ($\tau > 3 \times 10^8$ y) led by Phil Solomon. Another group led by Frank Bash posited that GMCs were young with ages $< 3 \times 10^7$ y old. At stake, among other things, was an understanding of how the clouds form and get destroyed. At the star formation discussion group I started at Berkeley, Frank Shu argued convincingly that GMCs were young and I encouraged Frank to publish a paper on the subject. Frank agreed if I would be a co-author. One of the main issues was the fraction of the total gas at various radii in the Galaxy, with the long lifetime advocates requiring that the molecular fraction dominates and the short lifetime advocates arguing the opposite, since one of the key arguments had to do with mass flow between the two phases. Frank and I argued for the latter and we provided a number of other quantitative analytical arguments in the paper on GMC lifetimes. This became a hotly contested topic. Both sides agreed that an acid test would be to see if GMCs were confined to spiral arms in grand design spirals, but it took some years before millimeter-wave interferometers were good enough to map GMCs in other galaxies and provide answers. Ultimately,
it became clear that for most of the disk, the atomic gas dominated and that GMCs are indeed concentrated in spiral arms.

Q: In 1982 you and Michel Fich and Tony Stark published a very high-impact paper on CO radial velocities toward HII regions. What was the origin of this project?

A: Just before I started my postdoc, I was trying to figure out what I was going to do at Berkeley. A group of Canadians led by Tony Moffat had just published the distances to many distant O stars in the outer region of the Milky Way. I knew from my thesis that O stars were almost always associated with molecular clouds whose radial velocities could be measured with high accuracy. With the distances from the Canadians and the velocities from the molecular clouds, I realized one could measure the rotation curve of the outer Galaxy. The rotation curve was a hot topic in those years because Vera Rubin and others showed that spiral galaxies tended to have flat rotation curves, implying that there was a lot of dark matter around. After showing that the rotation curve of the Milky Way was flat to interesting distances from the center, to make further improvements required going as far out as possible and covering as much Galactic azimuth as possible. Because there had been a lot of work on star clusters and OB associations, the limiting factor seemed to be getting accurate velocities to the associated molecular clouds. Because we could measure the velocities to the molecular clouds even when the O star distances had not yet been determined, we published the catalog of velocities to the HII regions lit up by the O stars whose distances were yet to be measured.

Q: A few years later you, with Loris Magnani and Lee Mundy, took an interest in high-latitude molecular clouds. What were your main results?

A: That project started from a comment made by Lyman Spitzer when I was visiting Princeton. Lyman said that all molecular clouds were in the Galactic plane which was why they were not seen at high latitude. I thought I would test the result by having Loris look through all of the Palomar-Schmidt photographs for evidence of uncatalogued weak obscuration toward which we would look for CO. Paul van den Bout, the director of the millimeter-wave observatory of the University of Texas, gave us some time and when I went to sleep I told Loris that the run would be a success if we detected 10 clouds. When I awoke, Loris told me that he had about 125 detections(!) proving that he was quite expert at finding weak obscuration. The main results were that the clouds existed at all and that they are the molecular clouds closest to the Sun. We were able to show was that molecular clouds were not self-gravitating and therefore had to be quite young, $\sim 10^8$ y old. The turbulent pressure in the clouds was larger than that of the interstellar medium and the clouds therefore had to form in overpressured regions perhaps in weak shocks. They are largely free of star formation and there is no "dark matter" such as anomalus dust to provide the gravitational binding. One could use the clouds to provide additional evidence that the Sun lies about 20 pc above the midplane of the Milky Way.

Q: You have made a number of studies of the rotation curve of the outer Milky Way, notably with your former student Jan Brand.

A: I met Jan when I was on a visit to Leiden in the summer of 1982. His original thesis plans had fallen through and he was casting around for something else to do. His original plan was to mount a 1mm receiver on an optical telescope and do molecular line observations using it. The problem was that there were so many reflections that it was impossible to get decent spectra and calibrate the lines. But to measure the Galactic rotation curve, one needed only accurate velocities not intensities. So I suggested to Jan that we use the receiver, which was going to be deployed on one of the ESO telescopes, to measure the outer Galaxy rotation curve in the southern hemisphere. As it turned out, we got time in Australia for this project on a proper millimeter-wave telescope and completed the project there. By this time, we had done all we could on the rotation curve using CO and put the northern and southern hemisphere data together to get a composite rotation curve (we also measured the two dimensional velocity field of the outer Galaxy which allowed one to correct kinematic distances for deviations from circular motion). The composite curve was almost dead flat as was observed in other galaxies.

Q: The shape of the Galaxy and the presence of a bar has been the subject of several of your papers. What are the key issues?

A: Shortly after publishing my first paper on the outer Galaxy rotation curve, Carl Heiles suggested I reanalyze the distribution of atomic hydrogen using the data in the Weaver and Williams HI survey, which at that time was the best available. I was interested in measuring the location and pitch angle of the spiral arms but in addition, I found that the outermost edge of the HI distribution showed a spatial "scalloping" with a wave number of about 10 around its circumference. This led to a long-standing interest in the true shape of the Milky Way as traced by the stars and the gas. A breakthrough was achieved with the publication of the Leiden-Argentina-Bonn or LAB survey which provided a uniform survey of the HI around the entire sky and also corrected for the effects of sidelobe contamination. The survey also made it possible to look at the distribution of gas out of the Galactic plane. So, armed with a reliable rotation curve, with Evan Levine, and Carl Heiles, we reanalyzed the distribution of atomic hydrogen in the outer Galaxy. In passing, we were able
make a face-on view of the Galaxy using the technique of
unsharp masking and were able to map out the four spiral
arms from the Solar Circle out to the edge of the stellar
disk. Equally important, we showed that the warp of the
Milky Way HI, which looks quite complex, was actually
a superposition of three and only three vertical modes.
This allowed Martin Weinberg to make a dynamical model of
this “ringing” of the disk. What surprised me just as
much, though, is that the thickness of the disk of gas on
one side of the Galaxy is a factor of two greater one side
than the other. This unstable situation must be dynami-
cally driven somehow, but it remains unexplained.

The story of the bar is quite different. David Spergel and
I had been working together on a couple of Milky Way
projects when the COBE map of the Galaxy was released.
Getting an early copy of the image from Mike Hauser, I
was blown away by how beautiful it looked and rushed up
to Princeton to show David this fantastic image. We im-
mediately started discussing various aspects of the image.
David produced a model of the emission and was able to
show that if there was a bar, there would be subtle differ-
ences in the image on either side of the Galactic center.
Notably, there would be a hole in the brightness distri-
bution in the differential plot. The trouble was that the
COBE data were not yet available so we could not check
the model. It turned out that the Japanese had published
an infrared image of the bulge, and when we made a dif-
ferential plot of the data, it showed just the features that
David’s model had predicted for a bar. Shortly afterwards
several other groups had found evidence for the bar, but
it was not until Eli Dwek had made a proper analytical
model for the bar and presented it at a meeting on the
Milky Way that we were satisfied that what we had done
was correct.

Q: You and Erik Rosolowsky have argued that hydrostatic
pressure determines the ratio of atomic to molecular gas
at a given radius in a galaxy. Have these ideas since been
tested?

A: Yes. Adam Leroy together with Fabian Walter’s group
at Heidelberg, looked at several different mechanisms to
get the ratio of atomic to molecular gas in a galaxy, and
found that the best predictor was the midplane hydro-
static pressure. More recently, Mark Krumholz and collab-
orators have sought to add another ingredient to the recipe
by arguing that metallicity is also important because low
metallicity reduces the shielding around molecular clouds
producing more HI for a given location and pressure in
the plane of a galaxy. As of now, there is evidence for
both points of view which are not incompatible with one
another. The galaxies we looked at all had essentially so-
lar metallicity so we couldn’t check Krumholz’s ideas with
the data we had. A number of tests are yet possible and
some of them are currently under way.

Q: You and your collaborators have suggested that high-
velocity metal-poor HI clouds are the building blocks of the
Local Group galaxies, and that they govern the chemical
evolution of the Galactic disk. Do present-day observa-
tions support this scenario?

A: That the High Velocity Clouds affect the chemical
evolution of the Galactic disk seems to be without ques-
tion. Essentially all measurements of the metallicity of the
clouds show them to be low metallicity, from 1/3 to 1/10
solar. That fact alone shows that their origin cannot be in
the Galactic disk, returning the gas in a galactic fountain,
lest the HVCs be of solar or greater metallicity.

Our paper on HVCs is one of my favorite papers even
though a central tenet is not supported by the observa-
tions. My interest in HVCs dates back to graduate
school when I searched unsuccessfully for CO in them.
Returning to the subject much later, we had convinced
ourselves from a number of different arguments that the
clouds had to have an extragalactic origin. We then wrest-
tled with the idea that the clouds were self-gravitating
and held together by dark matter. If this were the case,
then the HVCs are the gaseous components of dark matter
minihalos, which were being seen in cosmological simula-
tions. David Spergel made a cosmological model which
had the present day positions and radial velocities of the
Milky Way and M31 as the end point in the simulations.
The model implied that the HVCs are the leftover building
blocks of the Local Group. As it turned out, the distribu-
tion on the sky and the velocities matched the observations
pretty well without any fine-tuning of the models. A key
point of the models was that the self-gravity of the dark
matter provided the gravitational binding of the clouds if
the clouds existed for a Hubble time, requiring the clouds
to be on average at a distance of ∼500 kpc. The acid test
was whether such clouds were seen in sufficient numbers
in other galaxies. However, deep searches for stars in the
clouds, as well as deep searches for HVCs in other galaxies
turned up little, indicating that the HVCs were not self-
gravitating objects and therefore were probably more local
transient objects. The paper nevertheless remains one of
my favorites because it was a plausible early attempt to
explain the long-standing problem of the nature of HVCs
in a cosmological context.

Q: What are your current interests?

A: I’ve been interested for some time in star formation in
nearby galaxies. I’d like to know how environment affects
how stars form both within galaxies and between galaxies
of different type, for example in early- and late-type galax-
ies. I’m also interested in how dark matter is distributed
in dwarf spiral galaxies. The dwarf galaxies seem to be
the most dark matter dominated objects in the universe,
and they afford the greatest opportunity to learn about
the dark matter properties of galaxies.
Introduction

The L1551-IRS 5 source and its associated molecular and atomic outflow have been in focus of front-line research for at least the last 40 years. It was the first object I observed professionally and wrote my first paper on it. Opus No.1 as it were. I found it so interesting that after my my thesis about its molecular outflow I have now published more than 20 papers about this object and I am still fascinated by it.

I find it a very important object to study because of its proximity and orientation, and its display of basically all tracers of (low-mass) star formation such as its location at the edge of a dense molecular cloud and its associated Herbig-Haro objects. It has an atomic jet and an aligned molecular outflow that displays well separated blue- and red-shifted outflow lobes. The orientation of the outflow is thus at a shallow angle with respect to the plane of the sky making the resolution of small spatial elements possible. Like the majority of stellar systems, the source IRS 5 is even a binary, each component of which have a solar-system size protostellar disk (Bieging & Cohen, 1985; Rodríguez et al., 1986; Looney et al., 1997; Rodríguez et al., 1998), or maybe even a triple star system (Lim & Takakuwa, 2006). Apparently each of the components have its associated atomic jet (Fridlund & Liseau, 1998), and it has been suggested that there is also individual molecular outflows coming from each component (Wu et al., 2009). This assembly is wrapped inside a larger disk (of roughly Kuiper-Edgeworth belt dimensions) which in itself is found inside a rotating, flattened, molecular gas envelope of Oort cloud dimensions (Fridlund et al., 2002).

The two atomic jets emanate from IRS5 A and B and can be traced for some thousands of AU (tens of arc seconds). IRS5 and its associated jet(s) is also one of the first Herbig-Haro type sources where X-ray emission has been discovered (Favata et al., 2002). Herbig Haro jets can thus carry enough energy to create X-ray sources that can be used to further study important physical parameters of low mass jets and their interaction with the ambient medium, and even on short timescales (Favata et al., 2006).

All of this together make the L1551 IRS 5 object a marvellous laboratory in order to study the early phases of star formation and especially how the angular momentum of a collapsing cloudlet is the driving engine for a large number of phenomena accompanying this process. While stellar formation may be understood in principle, much of the details remain unknown, partly because it takes place hidden behind large amounts of extinction, requiring the development of more and more sophisticated techniques in the IR. It would be impossible to cover everything that has been studied and written about this fascinating object here. There are much more than 100 refereed papers written primarily about different aspects of L1551 IRS5 and its associated objects between 1979 and now. Therefore such an endeavour will have to await a proper review article (which appear to be well motivated), and the present article will have to be more of a personal account, sampling certain aspects of L1551 IRS 5.

The molecular cloud L1551

This molecular cloud was noted more than 60 years ago. Herbig obtained the first photographic plates of the region in 1951 (Cudworth & Herbig, 1979), and Sharpless (1959) listed the brightest optical nebulosity visible against the cloud as number 239 (the T-Tauri nebulosity is No 238) in his catalogue of HII regions. The molecular cloud L1551 itself is about 30 arc minutes across (Lynds, 1965), and over the years a number of other important young objects such as L1551 NE, HL & XZ Tau, the HH30 disk and its associated jet, IR sources and eventually several molecular outflows and Herbig-Haro objects have become associated with this cloud. In this article I will restrict myself almost exclusively to L1551 IRS 5 and its associated objects. Under the name of S239, Knapp et al. (1976) carried out very early CO and $^{13}$CO observations with the 11m NRAO telescope at Kitt Peak. They found large velocity gradients which they interpreted as the signature of infall of the whole cloud (about 100 $M_\odot$ of molecular material). These observations led Snell et al. (1980) to make a more detailed study of these molecular tracers, using the 4.9m MWO antenna in Texas, and mapping the kinematics they discovered the first of many bipolar molecular outflows.

Strom et al. (1974) studied HH objects with the objective of acquiring more information about the embedded IR sources that had been discovered during several surveys.
in the late 1960s, and for this purpose they included the HH28, HH29 and HH102 objects. HH102 (ex S239 – see Mundt et al. 1985) turns out to be a reflection nebula, not an HH object (large yellowish nebula to the upper right in Fig.1). Strom et al. (1976) identified a 2.2µm source, that became known as IRS 5. More or less simultaneously, Cudworth & Herbig (1979) had observed two Herbig-Haro objects clearly associated with the L1551 cloud, HH28 and HH29, and, comparing their data with photographic plates obtained in the beginning of the fifties, found that HH28 and HH29 showed significant proper motions. The proper motion vectors also appeared to intersect, when plotted backwards several hundred years in time, at the position of the IRS 5! Finally, again more or less simultaneously, Sandqvist & Bernes (1980) had published observations at 2-mm, 2-cm and 6-cm of H₂CO, formaldehyde, that could be modelled as an excellent tracer of density enhancements in molecular clouds, and found a density knot exactly on the position of L1551 IRS 5. This peak in the density indicated that we were dealing with a heavily embedded object, which made it a very nice target for observations in the far infrared (FIR). And Sandqvist & Bernes were in Stockholm....

**Balloon observations from Texas....**

At the end of 1978 I was just finishing my undergraduate studies in Stockholm and was thinking about what to do next when I was approached by Lennart Nordh (then at the Stockholm Observatory) who wanted to know if I was interested in a job. Three weeks later I had moved to Groningen in Holland and was busy acclimatising myself in the FIR balloon group there. Fast forward another five months (May 1979) and I was sitting at the National Center for Atmospheric Research (NCAR) balloon base in Palestine, Texas, carrying out my own first observation of L1551 IRS 5 with a balloon borne 60cm telescope, hanging under a balloon the size of a football field, and operating at 42 km altitude. The photometer had filters transmitting between 72µm and 196µm. From these observations we derived a total flux from IRS 5 of 25 solar luminosities (Fridlund et al., 1980), assuming a distance of 150pc, (L1551 is today considered to be at a distance of...
140 pc (Kenyon et al. 1994). So the conclusion was that it was a low mass pre-main-sequence stellar object, associated with the molecular outflow. I remained in Holland until 1981 working on a total of 6 balloon flights observing mainly compact, embedded HII regions. When I returned to Sweden in early 1982 I had a lot of material for my theses but my advisor (again Lennart Nordh) argued that the launch of the IRAS satellite just around the corner could possibly make my thesis obsolete. He suggested follow-up observations of 1-5\(\mu\)m NIR of my sources, as well as using the 20m mm-telescope at Onsala, Sweden for CO and \(^{13}\)CO observations with much higher spatial resolution than achieved by Snell et al. (1980).

Figure 2: R-band HST image of the HH 154 southern and northern jets in 1996.

Figure 3: HST image of the HH 154 jet in 1996 in the H\(\alpha\). The superimposed contours define the knots within the jet at different epochs: 1996 (blue), 1998 (green), and 2005 (red).

...Ground-based and satellites

The NIR observations carried out with the InSb photometer on the ESO 1m telescope in La Silla indicated that IRS 5 had lost more than 1/2 a magnitude in the K-band (2.2\(\mu\)m) with respect to the observations carried out by Strom et al. (1976) which could be indications that a FU Orionis type outburst had taken place recently (Fridlund et al., 1984b; Fridlund, 1987). The CO observations took place under some of the best conditions ever experienced at Onsala and I got beautiful data (Fridlund et al., 1984a). It was obvious to me that this was what my thesis should really be about and I should map the complete outflow at high spatial resolution. As mentioned above, the red- and blue-shifted CO outflow lobes are spatially well separated and have an angular extent of more than 20 arcminutes on the sky. The beam size of the Onsala 20m at the 2.6mm wavelength of CO/\(^{13}\)CO is 30" and I was planning to use a beam spacing of 20" so it was a large project under any conditions, and since the exceptional conditions experienced during my first run never rematerialised it meant that I did not finish the mapping of the blue-shifted outflow lobe until 1986. Those results were published half a year later as my PhD thesis (Fridlund, 1987). The red-shifted outflow lobe was eventually only partially sampled by me. My results demonstrated, nevertheless, clearly that the molecular outflow is mainly composed of the swept-up gas along the surface of the outflow lobe, a result that was confirmed by a more complete study by Moriarty-Scheiven et al. in a series of papers (1987a, 1987b, 1988). The outflow thus has the structure of evacuated edge-enhanced lobes, but it was found around this time that these lobes are filled with neutral atomic (HI) gas participating in the outflow (Lizano et al., 1988). Parenthetically, in January 1983 The Infrared Astronomical Satellite (IRAS) was launched. This was the first-ever space-based observatory and during ten months (until the liquid He cooling the whole spacecraft boiled off) it mapped essentially the whole sky at 12, 25, 60 and 100\(\mu\)m wavelength. Although it produced much better quality data than our balloon telescope, not a single one of our results were changed except providing smaller error bars. IRAS did, however, discover a new embedded FIR source, that became known as L1551 NE about 2.5 arcminutes away from IRS 5 and much weaker – only 9 \(L_\odot\) (Emerson et al., 1984). I remembered something when reading this paper, and looked up the original data from the balloon flight in 1979, and there was L1551 NE, just next to IRS 5 and just barely spatially resolved from it – but with a S/N of only 2.5 (although seen in independent scans in both filters)! So sometimes noise is data (and vice versa) and one has to know which is which.

In the meantime a lot had happened also in the visual wavelength range. Image intensified photographic plates
and the first CCD detectors had become available. With such detectors, optical studies could be carried out in a fraction of the time previously needed when using photographic plates alone. In a large study, the nebulosity very near (< 10 arcseconds) IRS 5 was interpreted as either a jet or an edge-enhanced cavity by Mundt & Fried (1983), who also found that it possessed a very knotted structure. Further studies by Mundt et al. (1985) who obtained spectra of the HH 102 found characteristics of a reflection nebulosity that displayed FU Orionis characteristics (i.e. P Cygni profiles) that they could associate with IRS 5. This was consistent with the 1-5µm observations by Fridlund (1984b, 1987). Sarcander et al., (1985) carried out a spectroscopic investigation of the IRS5 jet (as well as the HH28, HH29 and HH102 nebulosity) and found very high radial velocities in the brightest knot in the jet, as well as being able to estimate the density of the jet for the first time, and calculate that the jet only possessed at most 1% of the required momentum to drive the molecular outflow. Neckel & Staude (1987) then obtained new imaging data and comparing with the old images from Mundt & Fried in 1983, they could detect clear morphological changes in the jet consistent with the velocities > 200 km s\(^{-1}\) found in the spectroscopy of Mundt et al (1985) and the proper motions of Sarcander et al (1985). Stocke et al. (1988) also studied the jet spectroscopically confirming the high radial velocities and also finding strong indications that the visual extinction towards IRS 5 itself could be as high as 150 magnitudes or more. Given the geometry of the outflow, as well as the presence of the HH objects and their velocity vectors, this could immediately be interpreted as having a dense dusty disk orbiting the protostar and being viewed edge on (at right angles to the major axis of the outflow). Observations in the near IR (Campbell et al. 1988) could also be interpreted in this framework. Almost all of the Herbig Haro objects are located within the 'blue' CO lobe. The most prominent objects are HH28, HH29 and HH102 are also found within the cavity walls of the 'blue' lobe. Also the IRS 5 jet, which has Herbig Haro characteristics (beginning with Sarcander et al. (1985) and which led to it receiving the designation HH154 in the compilation of Reipurth 1999). Essentially only HH262 (López et al., 1998) can be found within the 'red' lobe. That more objects are visible in the 'blue' lobe is not so strange since apparently the outflow is emanating out of the cloud here while the 'red' lobe is penetrating into the L1551 cloud itself experiencing a progressively higher extinction. Liseau et al. (2005) found that the outflow is oriented with its major outflow axis most likely at an angle of between 45 and 60 degrees w.r.t. the plane of the sky. The velocity gradients found in CO (Fridlund et al., 1984a), as well as the radial velocity field of both HH29 and that found in the jet (Fridlund & Liseau, 1998; Fridlund et al., 1998), then made it very clear that the outflow that is originating at IRS 5 is interacting with the ambient medium at the position of the HH objects. The proper motion vectors of HH 28 and HH29 had also been found to intersect at IRS 5 when projected backwards in time by Cutworth & Herbig (1979). By observing HH29 (which is unusually bright for an HH object) with the International Ultraviolet Explorer (IUE) satellite, Liseau et al. (1996) found that the individual knots within HH 29 were varying by large factors over times less than 6 weeks (interval between observations). This indicated a very small size scale for the interacting elements, and a time scale for the shocking gas to pass through ambient knots (which must have a density enhancement of at least 10\(^3\) to produce the UV spectrum), of less than 6 weeks.

It should be noted that Devine et al. (1999, 2000) have found that there appear to be more outflows somewhat criss-crossing each other in the region and those authors argue that some of the HH objects, specifically HH28 and HH29, could be excited by a flow from another YSO (most probably L1551NE). More studies are needed to clarify this. Here we only note that both HH28 and HH29 are spatially within the 'blue' lobe of the outflow originating at IRS 5, as defined by the molecular studies, and this outflow is without doubt the most energetic in the region. The proper motion studies by Cutworth & Herbig (1979) also support this scenario (see below).

Because of the advent of a new detector developed by ESA for the Hubble Space Telescope another opportunity arose. I was now (since 1989) working for ESA and one of my tasks was to take a development of this HST detector and test it on the ground. The detector was a very sensitive photon counting detector, which equipped with very narrow band filters could be used to study the emission lines in nebulae quantitatively. Bringing this instrument to the Nordic Optical telescope in La Palma, Spain, we began by observing HH29 in a number of shock diagnostic emission lines (Fridlund et al., 1993) and continued with observations of the IRS 5 jet, now using a CCD camera instead since they had become more sensitive (Fridlund & Liseau, 1994), where we confirmed and extended the work of Neckel & Staude (1987). The results were so promising it led us to propose a multi-cycle program on the HST with its high spatial resolution. We followed up our observations of HH29 with a program further clarifying the physical parameters such as densities and velocities using the NTT/EMMI echelle spectrograph at ESO, La Silla. We found densities in the individual knots of HH 29 of 10\(^3\) cm\(^{-3}\) - 10\(^4\) cm\(^{-3}\) within an 'inter-clump' medium with a density of about 300 cm\(^{-3}\), as well as radial velocities of up to 200 km s\(^{-1}\).

The binary of IRS 5 was noted early (Bieging & Cohen, 1985; Rodríguez et al., 1986) in radio observations penetrating the extinction, although it was debated for a few
years whether one was observing a toroid shaped gas disk or the components in a binary. It was interferometric observations that finally could decide that this was a case of two stars being formed within the same envelope (Looney et al., 1997; Rodríguez et al., 1998) and eventually tracing the optical jets disappearing behind the obscuration, each towards one of the two components (Rodríguez et al., 2003a) and finally observing the proper motions of the components and determine their total mass to be 1.2 $M_\odot$ (Rodríguez et al., 2003b). These data were later used by Liseau et al. (2005) to model the physical parameters of the system further, arriving at stellar masses of 0.8 $M_\odot$ and 0.3 $M_\odot$ respectively.

**Into deepest space**

Our first set of HST WFPC2 observations were carried out in cycles 5 & 6, the results of which can be found in a series of papers. The first results were published in Fridlund & Liseau (1998). We confirmed the binarity of the jet and could connect it to the binarity of IRS 5 itself, as well as identify the two separate velocity systems belonging to the two jets. We further derived the structure of the working surface of the jet (HH154), resolving completely the Mach disk from the bow shock. Comparing with shock models, and having the radial velocities (from observations with the Nordic Optical Telescope) and an estimate for the proper motions of the working surface (from the results quoted above) it was possible to derive the electron density of the jet and we could (again) conclude the jet could not be the driver for the large scale molecular outflow since a) it is lacking at least two orders of magnitude in momentum and b) its dynamic age is 3 orders of magnitude too small thus confirming the results of Sarcanor et al (1985). In Fridlund et al. (2005) we presented the complete analysis of the HST data from these cycles. We found that the highest ‘true’ velocities within the jet were between 500 and 600 km s$^{-1}$ as well as mapping out the appearance, disappearance and apparent movements of different features within the jet. Specifically we found that the Mach disk of the working surface is moving downstream at a transverse velocity of 180 km s$^{-1}$. In 2002 we observed L1551 with ESA’s X-ray satellite XMM. I was expecting, based on the strong shock characteristics we had found in HH29, that it was most likely that we would find any X-rays there. It was, however, within the jet itself that we discovered an X-ray source (Favata et al., 2002) Later observations (Bally et al., 2003 and Favata et al., 2006) demonstrated that the position of the X-ray source is about 0.8 arc seconds away from IRS 5 itself (about 100 AU), just where the jets emerge from behind the optical extinction. Representative of shock temperatures of 4MK, it appears just where we observe ‘true’ velocities of 500 to 600 s$^{-1}$.

**Molecules again**

We observed the inner 3 arc minutes by 3 arc minutes around IRS 5 in a number of molecules, HCO$^+$, H$^{13}$CO$^+$, $^{12}$CO and $^{13}$CO, all in the J=1-0 transition, using the Onsala 20m telescope and acquiring very high signal to
noise observations (Fridlund et al., 2002). By using all these isotopomers we could determine the total mass of the gas, its kinematics and the general structure in a region about the size of the Oort cloud in the Solar System. By tracing the self reversal in the HCO$^+$, we believe we have defined the mid plane of the disk. The H$^{13}$CO$^+$, on the other hand is optically thin or near so and have been used to calculate the mass of the disk and its surrounding envelope, which turns out to be about 2.5 $M_\odot$ (excluding the protostars). Kinematically most of this molecular material appears to be rotating, an observation strongly supporting that of Kaifu et al (1984) which was based on observations of CS with the Nobeyama 45m telescope. We also find that the molecular outflow has a very high mass loss rate, $10^{-5}M_\odot$ yr$^{-1}$ confirming the result of Fridlund & Knee (1993).

We also searched for gas phase methanol (CH$_3$OH) and HCN, in the direction of L1551 IRS 5 expecting to see it only directly at the position of the protostar itself, since it should freeze out under the conditions of the disk/envelope. Surprisingly we discovered it essentially all along the rotating flattened envelope (White et al., 2006, see Fig. 5). The only observable heat source that could provide the UV or harder photons is the jet, and modelling the geometry of the situation and knowing the flux of HH154, we found that radiation from the jet could sufficiently heat the surface of the disk tens of thousands of AU away from the jet base.

I would like to finish with some general thoughts about what we see in the area around L1551. Many sets of data covering wavelengths from the X-ray region to cm radio wavelengths are in agreement that some very energetic processes are taking place here at different spatial scales. One may assume that the energy required for these processes is coming from the accretion process, but the gravitational energy released from the collapse of the part of the cloud forming IRS 5 is only part of it. The rotational energy from the large flattened envelope has to be removed as the gas is slowly accreting towards the centre of the forming star system. There is a tremendous amount of angular momentum that need to be transferred into the outflow. The mechanism doing this is still unknown. There may also be a large amount of magnetic energy 'frozen' into the rotating gas envelope, and where the diffusion time is significantly longer than the star formation process. The molecular outflow seems to have 2-3 orders of magnitude more momentum than the optically visible atomic jet could deliver to it so it can not – at least not currently – be providing all the input of energy needed into the outflow. There are three components of the outflow that need to be coupled together. The visible jet with velocities of up to more than 500 km s$^{-1}$, the HI flow filling the swept-up cavity with velocities around 150 km s$^{-1}$ and the molecular outflow towards the edges with velocities of around 10-50 km s$^{-1}$. All of these issues, which probably also occur in other star forming regions during the outflow phase, are, in my opinion, elements where the continuing study of L1551 IRS 5 may bring further clarity.

This source has continued to surprise me for a very long time now and I am certain that new observations, especially with ALMA, and additional monitoring in the optical and X-rays will continue to do so.

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1. Introduction

Throughout their evolution, low-mass stars lose angular momentum. A typical young star contains several orders of magnitude less angular momentum per mass unit than the molecular cloud core from which it has formed (Bodenheimer 1995). Another couple of orders of magnitude are lost on the main sequence. Through the RGB phase, the angular momentum disposal continues. The white dwarf at the end of the timeline incorporates even less specific angular momentum than the late main sequence star (although we do not quite know by how much, Kawaler 2004). Basically, angular momentum conservation is very rare in the evolution of low-mass stars.

The main agent in the rotational braking of a low-mass star is the stellar magnetic field. During the T Tauri phase, the magnetic interaction between star and disk effectively prevents the spin-up of the star that would otherwise be expected due to contraction and mass infall. For the first few million years of their existence, a significant fraction of low-mass stars rotate with approximately constant period (e.g., Rebull et al. 2004, Herbst & Mundt 2005, Davies et al. 2014). The exact physical mechanism that allows them to do that is not quite clear, but is likely to be a combination of magnetic locking of star and disk as well as powerful winds (see Matt et al. 2010, 2012). Mag- netically driven stellar winds control the rotation for the remainder of the pre-main sequence and the entire main sequence phase. On the main sequence, stellar angular momentum as well as indicators related to magnetic activity drop approximately with the square-root of the age, a relation known for more than 40 years (Skumanich 1972).

Stellar rotation is interesting because it is deeply linked to many important physical aspects of stellar evolution — magnetic field generation, interior structure, disk evolution, winds, internal mixing, chemical evolution, as well as magnetic activity which has implications for habitability of planets. Also, the rotation period, measured from the periodic photometric modulation due to surface features, is one of the very few fundamental stellar parameters that can be derived for large numbers of stars with percent or better accuracy, completely independent of models. This makes it very tempting to use rotation as a secondary indicator to infer other parameters, for example, to estimate stellar ages, an area of research that has been coined gyrochronology (Barnes 2003).

Because of the propensity of low-mass stars to shed angular momentum, it is always interesting to study objects that buck the trend and manage to conserve or almost conserve angular momentum for significant periods of time. These objects give us information about the mass dependencies of the fundamental processes mentioned above, specifically, they tell us in which parameter regimes these processes fail. Planets are in this category, as are brown dwarfs, objects unable to sustain stable Hydrogen fusion and to attain thermodynamical equilibrium, with masses below 0.08 \( M_\odot \). In this article I will give a summary of this exciting topic within the venerable research field of stellar rotation. I will mostly discuss the rotational evolution of young brown dwarfs (since this is the Star Formation Newsletter) and only briefly touch on the (equally exciting) topic of the rotation of evolved field brown dwarfs and the link to cloudy atmospheres (see Radigan et al. 2014, Metchev et al. 2015 and references therein).

For more details on everything that is cursorily summarised here, I refer the reader to the reviews in Protostars & Planets V by Herbst et al. (2007) and in Protostars & Planets VI by Bouvier et al. (2013). The former is heavily focused on observations and limited to the pre-main sequence stage, while the latter also includes a thorough overview of the theory side as well as the main-sequence evolution.

2. Observational timeline

The exploration of the rotation of very low mass stars and brown dwarfs lagged only a few years behind the discovery of these objects. In the mid and late 90s, several groups reported solid evidence that objects at the bottom of the main sequence and beyond are fast rotators (e.g., Basri & Marcy 1995, Martin 1998, Terndrup et al. 1999, Bailer-Jones & Mundt 1999). The first \textit{slowly} rotating brown dwarfs with periods of several days were published by Jørgens et al. (2003) and Scholz & Eisloffel (2004, 2005) for objects in young clusters and star forming regions.

Rotation periods in young clusters are the low hanging fruit in this field. The dense populations of these regions allow for very efficient, multiplexed, deep, high-cadence
monitoring, using wide-field imagers at medium-sized telescopes. In addition, young brown dwarfs are late M dwarfs which exhibit significant magnetic spot activity, facilitating the measurement of rotation periods. Today we know periods for dozens substellar objects with ages of 1-5 Myr (see Fig. 1), primarily thanks to a number of PhD projects devoted to studying the variability of young stars and brown dwarfs. This includes my own PhD work published in Scholz & Eislöffel (2004a, b, 2005, 2009, 2011), but also the work by Markus Lamm (Lamm et al. 2004, 2005), Maria Victoria Rodriguez-Ledesma (Rodriguez Ledesma et al. 2009, 2010) as well as Ann Marie Cody (Cody & Hillenbrand 2010, 2011, 2014). Some further periods for young brown dwarfs have been published by Bailer-Jones & Mundt (2001), Zapatero Osorio et al. (2004), Caballero et al. (2004), and Scholz et al. (2012).

Earlier this year, we have used high-precision lightcurves from the revamped Kepler mission K2 to measure rotation periods for 16 young objects with masses close to or below the Hydrogen burning limit (Scholz et al. 2015, see Fig. 1). These are members of the Upper Scorpius star forming regions, with ages between 5 and 10 Myr, a previously unexplored age regime for brown dwarf rotation. Recently Biller et al. (2015) constrained for the first time the rotation period of a young brown dwarf with a mass below the Deuterium burning limit (lower limit of 5h).

In all young regions studied so far, the brown dwarf periods range from a few hours up to several days. Note that some of the published periods at ages of 1-5 Myr are in the range of the breakup limit. If confirmed, this would have severe implications for the further evolution of these brown dwarfs (see Scholz & Eislöffel 2005).

Measuring periods for field brown dwarfs is more difficult, because they have to be monitored one by one. Also, the origin of periodic variability is different in the older, and therefore much cooler, field brown dwarfs. Their variability is most likely caused by inhomogenous cloud coverage (‘weather’), instead of magnetic spots. While a few individual periods have been published earlier, the discovery of highly variable brown dwarfs at the L/T transition by Artigau et al. (2009) and Radigan et al. (2012) increased the interest in brown dwarf variability and motivated a number of monitoring projects for field brown dwarfs aimed at studying cloud properties, which resulted, almost as a side-product, in many known rotation periods (e.g., Radigan et al. 2014, Metchev et al. 2015). So far, the overwhelming majority of the published periods for field brown dwarfs are short – less than 20 hours – but there are some exceptions (see Metchev et al. 2015). Since the monitoring runs for most objects have also been short, the upper limit for brown dwarf periods remains poorly defined.

This overview is focused on photometrically measured rotation periods. In comparison with spectroscopic rotational velocities, they have the advantage of being much more accurate and free of the inclination factor. However, incompleteness and bias in period samples is always an issue, as periods can only be inferred when asymmetrically distributed surface features are present. Therefore it is important to note that the record of rotational velocities available for brown dwarfs at various ages (e.g., Bailer-Jones 2004, Zapaterio Osorio 2006, Reiners & Basri 2008, Konopacky et al. 2012) so far corroborates the findings from rotation periods.

3. Inefficient disk braking

Disk braking is a term I like to use for whatever disk-related mechanism that manages to keep the rotation periods of young stars ‘locked’ for ages of 1 to 5 Myr. Young brown dwarfs have much lower luminosities, lower accretion rates, lower disk masses, and (perhaps) different magnetic field properties than typical T Tauri stars. Testing disk braking in brown dwarfs is therefore a good way to illuminate how the braking mechanism works in a very different parameter regime.

The observational study of disk braking in brown dwarfs is still crippled by the lack of decently sized samples with measured rotation periods and mid-infrared photometry. The latter is essential to reliably test for the presence of the disk. In Scholz & Eislöffel (2004) we used the variability...
ity amplitude as indicator for accretion and, hence, disk, and find that the slow rotators all are accretors, which would be evidence for disk braking, but in a small sample which also included very low mass stars. Rodríguez Ledesma et al. (2010) find no connection between slow rotation and presence of the disk in their sample of ONC brown dwarfs, but they use near-infrared photometry as disk indicators. At near-infrared wavelengths, the photospheric emission of brown dwarf peaks and the disk is faint, which makes it very difficult to robustly detect the disk. Cody & Hillenbrand (2010) test the disk-rotation relation in the substellar regime for the first time with mid-infrared photometry and do not see evidence for a direct connection between rotation rate and the presence of a disk – but their sample only contains few brown dwarfs.

In our most recent study, we use the periods derived for brown dwarfs in Upper Scorpius in combination with literature data to trace for the first time the substellar rotational evolution from 1 to 10 Myr (Scholz et al. 2015). The 'money plot' from this paper is reproduced in Fig. 1 which simply shows periods vs. age in comparison with tracks assuming angular momentum conservation. We find that the period evolution over this age span is consistent with no angular momentum loss, i.e. no rotational braking at all. If disk braking occurs, the locking timescale is at most 2-3 Myr, significantly shorter than for low-mass stars. This finding is robust within the uncertainties for the cluster ages. However, we also identify the disk-bearing objects in our sample, using WISE photometry, and find that all objects in our sample which still harbour disks are among the slowest rotators. Thus, while disk braking seems to be very inefficient in brown dwarfs, as already found by Cody & Hillenbrand (2010) (and by Lamm et al. 2005 for slightly more massive objects), it does seem to be at work at least in a few selected objects which manage to retain their disks longest.

Since disk lifetimes in brown dwarfs are not vastly different from stars (see Dawson et al. 2013), these findings indicate that the interaction between star and disk changes as we go to very low masses. Low ionisation at the inner disk edge (due to lower luminosity), lower mass accretion rates, as well as changes in the magnetic configuration all seem plausible explanations at this stage, but this needs to be explored in detail. In any case, whatever braking mechanism is at work in low-mass T Tauri stars, it should become inefficient in the substellar regime.

4. Also: inefficient wind braking

Wind braking controls the long-term rotational evolution of solar-mass stars. By the time stars with spectral type F to K have reached the age of the Hyades (600 Myr), they have settled onto a well defined period-mass relationship, a kind of 'main sequence' of rotational evolution. At this point the rotation period of low-mass stars is a function of mass and age, and little else (at least once binary stars in tidal interaction have been eliminated). With decreasing mass, the time objects need to converge to the rotational main sequence increases substantially (Irwin et al. 2011, Scholz et al. 2012, Newton et al. 2015); at 0.1-0.3 M⊙, the spindown timescale is in the range of gigayears. The origin of this mass dependence is not well understood, but is likely related to the details of the wind physics and/or magnetic field generation.

The fast rotation of most field brown dwarfs indicates that this trend continues in the brown dwarf regime. Extrapolating from the evolutionary tracks for very low mass stars, we would expect brown dwarfs to retain their fast rotation rates for more than 5 Gyr. In addition to changes in magnetic field properties, most of the atmospheres of brown dwarfs eventually become too cool for an efficient coupling between plasma and magnetic field (Mohanty et al. 2003, Rodríguez-Barrera et al. 2015), which mostly shuts down persistent Hα and X-ray activity (apart from transient events) and may further impede rotational braking. Based on the currently known periods, however, there is evidence for some rotational braking on long timescales, but the angular momentum loss rate may be ~ 10000 times weaker than in solar-mass stars (Bouvier et al. 2013). Large and unbiased period samples of field brown dwarfs at various ages are needed to constrain this further. At this stage, however, it seems clear that wind braking in brown dwarfs does not work very well.

5. A universal spin-mass relation?

In terms of their rotational evolution, brown dwarfs are much more like giant planets than stars – they retain their initial rotation rates for cosmological timescales. Therefore, it makes sense to compare rotation rates of brown dwarfs with those of planets. Solar system planets which are not tidally spun down, e.g. Mars, Jupiter, Saturn, Uranus, Neptune, obey a surprisingly strict relation between equatorial rotational velocity and mass (e.g., Hughes 2003), shown in Fig. 2. The Earth falls slightly below this correlation due to tidal interaction with the Moon, but fits the line fairly well when the Moon 'is put back into Earth' (Hughes 2003). This impressive relation can also be extended towards lower masses by including asteroidal data. As shown by Snellen et al. (2014), the rotational velocity for the young, massive exoplanet β Pic b also falls on this spin-mass relation, at least given the errors on its mass. Note that a similar trend is also apparent when plotting angular momentum or specific angular momentum instead of rotational velocity. The relation is likely to be directly linked to the formation processes, presumably to the growth of planets in the protoplanetary disk.

In Fig. 2 I overplot the typical range of rotational velocities, inferred from periods, for field brown dwarfs (black line, based on a period range from 2 to 20 h, see Metchev
then conceivable that the few brown dwarfs that do not obey the spin-mass relation might be the exceptions that form like giant planets and are ejected at an early evolutionary stage from the disk. If this relation really holds for all young substellar objects formed in disks, a hypothesis we need to test further, this could help us to distinguish brown dwarf formation scenarios.

On the other hand, brown dwarfs do spin down, albeit slowly, which makes the interpretation of Fig. 2 more difficult. Planets not affected by tidal interactions might be the only objects in the Galaxy that retain their primordial rotation rate and conserve angular momentum. By including brown dwarfs in the spin-mass diagram, we see the subtle emergence of the mechanisms that are responsible for the efficient spindown of stars.

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Planetary System Formation in Protoplanetary Disk around HL Tauri

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We re-process the Atacama Large Millimeter/Submillimeter Array (ALMA) long-baseline science verification data taken toward HL Tauri. As shown by the previous work, we confirm that the high spatial resolution (\(\sim 0''019\), corresponding to \(\sim 2.7\) AU) dust continuum images at \(\lambda = 0.87, 1.3,\) and 2.9 mm exhibit a multiple ring-like gap structure in the circumstellar disk. Assuming that the observed gaps are opened up by currently forming, unseen bodies, we estimate the mass of such hypothetical bodies based on following two approaches; the Hill radius analysis and a more elaborated approach developed from the angular momentum transfer analysis in gas disks. For the former, the measured gap widths are used for calibrating the mass of the bodies, while for the latter, the measured gap depths are utilized. We show that their masses are likely comparable to or less than the mass of Jovian planets, and then discuss an origin of the observed gap structure. By evaluating Toomre’s gravitational instability (GI) condition and cooling effect, we find that the GI might be a possible mechanism to form the bodies in the outer region of the disk. As the disk might be gravitationally unstable only in the outer region of the disk, inward planetary migration would be needed to construct the current architecture of the hypothetical bodies. We estimate the gap-opening mass and show that type II migration might be able to play such a role. Combining GIs with inward migration, we conjecture that all of the observed gaps may be a consequence of bodies that might have originally formed at the outer part of the disk, and have subsequently migrated to the current locations. While ALMA’s unprecedented high spatial resolution observations can revolutionize our picture of planet formation, more dedicated observational and theoretical studies are needed in order to fully understand the HL Tau images.

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The Role of the Cooling Prescription for Disk Fragmentation: Numerical Convergence & Critical Cooling Parameter in Self-Gravitating Disks

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Protoplanetary disks fragment due to gravitational instability when there is enough mass for self-gravitation, described by the Toomre parameter, and when heat can be lost at a rate comparable to the local dynamical timescale, described by \(t_c = \beta\Omega^{-1}\). Simulations of self-gravitating disks show that the cooling parameter has a rough critical value at \(\beta_{\text{crit}} = 3\). When below \(\beta_{\text{crit}}\), gas overdensities will contract under their own gravity and fragment into bound objects while otherwise maintaining a steady state of gravitoturbulence. However, previous studies of the critical cooling parameter have found dependence on simulation resolution, indicating that the simulation of self-gravitating protoplanetary disks is not so straightforward. In particular, the simplicity of the cooling timescale \(t_c\) prevents fragments from being disrupted by pressure support as temperatures rise. We alter the cooling law so that the cooling timescale is dependent on local surface density fluctuations, a means of incorporating optical depth effects into the local cooling of an object. For lower resolution simulations, this results in a lower critical cooling parameter and a disk more stable to gravitational stresses suggesting the formation of large gas giants planets in large, cool disks is
generally suppressed by more realistic cooling. At our highest resolution however, the model becomes unstable to fragmentation for cooling timescales up to $\beta = 10$.

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Direct imaging of the water snow line at the time of planet formation using two ALMA continuum bands

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Molecular snow lines in protoplanetary disks have been studied theoretically for decades because of their importance in shaping planetary architectures and compositions. The water snow line lies in the planet formation region at $\lesssim 10$ AU, and so far its location has been estimated only indirectly from spatially-unresolved spectroscopy. This work presents a proof-of-concept method to directly image the water snow line in protoplanetary disks through its physical and chemical imprint in the local dust properties. We adopt a physical disk model that includes dust coagulation, fragmentation, drift, and a change in fragmentation velocities of a factor 10 between dry silicates and icy grains as found by laboratory work. We find that the presence of a water snow line leads to a sharp discontinuity in the radial profile of the dust emission spectral index $\alpha_{\text{mm}}$, due to replenishment of small grains through fragmentation. We use the ALMA simulator to demonstrate that this effect can be observed in protoplanetary disks using spatially-resolved ALMA images in two continuum bands. We explore the model dependence on the disk viscosity and find that the spectral index reveals the water snow line for a wide range of conditions, with opposite trends when the emission is optically thin rather than thick. If the disk viscosity is low ($\alpha_{\text{visc}} < 10^{-3}$) the snow line produces a ring-like structure with a minimum at $\alpha_{\text{mm}} \sim 2$ in the optically thick regime, possibly similar to what has been measured with ALMA in the innermost region of the HL Tau disk.

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Exploring Molecular Complexity with ALMA (EMoCA): Deuterated complex organic molecules in Sagittarius B2(N2)

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Deuteration is a powerful tracer of the history of the cold prestellar phase in star forming regions. Apart from methanol, little is known about deuterium fractionation of complex organic molecules in the interstellar medium, especially in high mass star forming regions. Our goal is to detect deuterated complex organic molecules toward the high mass star forming region Sagittarius B2 (Sgr B2) and derive their level of deuteration. We use a complete 3 mm spectral line survey performed with the Atacama Large Millimeter/submillimeter Array (ALMA) to search for deuterated complex organic molecules toward the hot molecular core Sgr B2(N2). Population diagrams and integrated intensity maps are constructed to fit rotational temperatures and emission sizes for each molecule. Column densities are derived by modelling the full spectrum under the assumption of local thermodynamic equilibrium. The results are compared to predictions of two astrochemical models that treat the deuteration process. We report the detection of CH$_2$DCN toward Sgr B2(N2) with a deuteration level of 0.4%, and tentative detections of CH$_3$DOH, CH$_2$DCH$_2$CN, the chiral molecule CH$_3$CHDCN, and DC$_3$N with levels in the range 0.05%–0.12%. A stringent deuteration upper limit is obtained for
A multi-wavelength interferometric study of the massive young stellar object IRAS 13481–6124

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We present new mid-infrared interferometric observations of the massive young stellar object IRAS 13481–6124, using VLTI/MIDI for spectrally-resolved, long-baseline measurements (projected baselines up to ∼120 m) and GSO/T-ReCS for aperture-masking interferometry in five narrow-band filters (projected baselines of ∼1.8–6.4 m) in the wavelength range of 7.5–13 µm. We combine these measurements with previously-published interferometric observations in the K and N bands in order to assemble the largest collection of infrared interferometric observations for a massive YSO to date. Using a combination of geometric and radiative-transfer models, we confirm the detection at mid-infrared wavelengths of the disk previously inferred from near-infrared observations. We show that the outflow cavity is also detected at both near- and mid-infrared wavelengths, and in fact dominates the mid-infrared emission in terms of total flux. For the disk, we derive the inner radius (∼1.8 mas or ∼6.5 AU at 3.6 kpc), temperature at the inner rim (∼1700 K), inclination (∼48°) and position angle (∼107°). We determine that the mass of the disk cannot be constrained without high-resolution observations in the (sub-)millimeter regime or observations of the disk kinematics, and could be anywhere from ∼10−3 to 20 MJ. Finally, we discuss the prospects of interpreting the spectral energy distributions of deeply-embedded massive YSOs, and warn against attempting to infer disk properties from theSED.

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First light of the VLT planet finder SPHERE. IV. Physical and chemical properties of the planets around HR8799

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The system of four planets around HR8799 offers a unique opportunity to probe the physics and chemistry at play in the atmospheres of self-luminous young (∼30 Myr) planets. We recently obtained new photometry of the four planets and low-resolution (R ∼ 30) spectra of HR8799 d and e with the SPHERE instrument (paper III). In this paper (paper IV), we compare the available spectra and photometry of the planets to known objects and atmospheric models (BT-SETTL14, Cloud-AE60, Exo-REM) to characterize the atmospheric properties of the planets. We find that HR8799d and e properties are well reproduced by those of L6-L8 dusty dwarfs discovered in the field, among which some are candidate members of young nearby associations. No known object reproduces well the properties of planets b and c. Nevertheless, we find that the spectra and WISE photometry of peculiar and/or young early-T dwarfs reddened by submicron grains made of corundum, iron, enstatite, or forsterite successfully reproduce the SED of these two planets. Our analysis confirms that only the Exo-REM models with thick clouds fit (within 2σ) the whole set of spectrophotometric datapoints available for HR8799 d and e for T_{eff} = 1200 K, log g in the range 3.0–4.5, and M/H= +0.5. The models still fail to reproduce the SED of HR8799c and b. The determination of the metallicity, log g, and cloud thickness are degenerate. We conclude that an enhanced content in dust and decreased CIA of H_{2} is certainly responsible for the deviation of the properties of the planet with respect to field dwarfs. The analysis suggests in addition that HR8799c and b have later spectral types than the two other planets, and therefore could both have lower masses.

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DR Tau: Temporal variability of the brightness distribution in the potential planet-forming region

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We investigate the variability of the brightness distribution and the changing density structure of the protoplanetary disk around DR Tau, a classical T Tauri star. DR Tau is known for its peculiar variations from the ultraviolet (UV) to the mid-infrared (MIR). Our goal is to constrain the temporal variation of the disk structure based on photometric and MIR interferometric data. We observed DR Tau with the MID-infrared Interferometric instrument (MIDI) at the Very Large Telescope Interferometer (VLTI) at three epochs separated by about nine years, two months, respectively. We fit the spectral energy distribution and the MIR visibilities with radiative transfer simulations. We are able to reproduce the spectral energy distribution as well as the MIR visibility for one of the three epochs (third epoch) with a basic disk model. We were able to reproduce the very different visibility curve obtained nine years earlier with a very similar baseline (first epoch), using the same disk model with a smaller scale height. The same density distribution also reproduces the observation made with a higher spatial resolution in the second epoch, i.e. only two months before the third epoch.

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Feedback from massive stars and gas expulsion from proto-Globular Clusters

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Globular clusters are considerably more complex structures than previously thought, harbouring at least two stellar generations which present clearly distinct chemical abundances. Scenarios explaining the abundance patterns in globular clusters mostly assume that originally the clusters had to be much more massive than today, and that the second generation of stars originates from the gas shed by stars of the first generation (FG). The lack of metallicity spread in most globular clusters further requires that the supernova-enriched gas ejected by the FG is completely lost within ~30 Myr, a hypothesis never tested by means of three-dimensional hydrodynamic simulations. In this paper, we use 3D hydrodynamic simulations including stellar feedback from winds and supernovae, radiative cooling and self-gravity to study whether a realistic distribution of OB associations in a massive proto-GC of initial mass $M_{\text{tot}} \sim 10^7 \, M_\odot$ is sufficient to expel its entire gas content. Our numerical experiment shows that the coherence of different associations plays a fundamental role: as the bubbles interact, distort and merge, they carve narrow tunnels which reach deeper and deeper towards the innermost cluster regions, and through which the gas is able to escape. Our results indicate that after 3 Myr, the feedback from stellar winds is responsible for the removal of ~40% of the pristine gas, and that after 14 Myr, ~99% of the initial gas mass has been removed.

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Classifying the embedded young stellar population in Perseus and Taurus & the LOMASS database

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Context. The classification of young stellar objects (YSOs) is typically done using the infrared spectral slope or bolometric temperature, but either can result in contamination of samples. More accurate methods to determine the evolutionary stage of YSOs will improve the reliability of statistics for the embedded YSO population and provide more robust stage lifetimes.

Aims. We aim to separate the truly embedded YSOs from more evolved sources.

Methods. Maps of HCO$^+$ $J=4–3$ and C$^{18}$O $J=3–2$ were observed with HARP on the James Clerk Maxwell Telescope (JCMT) for a sample of 56 candidate YSOs in Perseus and Taurus in order to characterize emission from high (column) density gas. These are supplemented with archival dust continuum maps observed with SCUBA on the JCMT and Herschel PACS to compare the morphology of the gas and dust in the protostellar envelopes. The spatial concentration of HCO$^+$ $J=4–3$ and 850 $\mu$m dust emission are used to classify the embedded nature of YSOs.

Results. Approximately 30% of Class 0+I sources in Perseus and Taurus are not Stage I, but are likely to be more evolved Stage II pre-main sequence (PMS) stars with disks. An additional 16% are confused sources with an uncertain evolutionary stage.

Conclusions. Separating classifications by cloud reveals that a high percentage of the Class 0+I sources in the Perseus star forming region are truly embedded Stage I sources (71%), while the Taurus cloud hosts a majority of evolved PMS stars with disks (68%). The concentration factor method is useful to correct misidentified embedded YSOs, yielding higher accuracy for YSO population statistics and Stage timescales. Current estimates (0.54 Myr) may overpredict the Stage I lifetime on the order of 30%, resulting in timescales of 0.38 Myr for the embedded phase.

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High Resolution 8 mm and 1 cm Polarization of IRAS 4A from the VLA Nascent Disk and Multiplicity (VANDAM) Survey

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Magnetic fields can regulate disk formation, accretion and jet launching. Until recently, it has been difficult to obtain high resolution observations of the magnetic fields of the youngest protostars in the critical region near the protostar. The VANDAM survey is observing all known protostars in the Perseus Molecular Cloud. Here we present the polarization data of IRAS 4A. We find that with $\sim0''2$ (50 AU) resolution at $\lambda = 8.1$ and 10.3 mm, the inferred magnetic field is consistent with a circular morphology, in marked contrast with the hourglass morphology seen on larger scales. This morphology is consistent with frozen-in field lines that were dragged in by rotating material entering the infall region. The field morphology is reminiscent of rotating circumstellar material near the protostar. This is the first polarization detection of a protostar at these wavelengths. We conclude from our observations that the dust emission is optically thin with $\beta \sim 1.3$, suggesting that mm/cm-sized grains have grown and survived in the short lifetime of the protostar.
Resolving the HD 100546 Protoplanetary System with the Gemini Planet Imager: Evidence for Multiple Forming, Accreting Planets

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We report Gemini Planet Imager H band high-contrast imaging/integral field spectroscopy and polarimetry of the HD 100546, a 10 Myr-old early-type star recently confirmed to host a thermal infrared bright (super)jovian protoplanet at wide separation, HD 100546 b. We resolve the inner disk cavity in polarized light, recover the thermal-infrared (IR) bright arm, and identify one additional spiral arm. We easily recover HD 100546 b and show that much of its emission originates an unresolved, point source. HD 100546 b likely has extremely red infrared colors compared to field brown dwarfs, qualitatively similar to young cloudy superjovian planets, however, these colors may instead indicate that HD 100546 b is still accreting material from a circumplanetary disk. Additionally, we identify a second point source-like peak at r_{proj} ~ 14 AU, located just interior to or at inner disk wall consistent with being a 10–20 MJ candidate second protoplanet—“HD 100546 c” —and lying within a weakly polarized region of the disk but along an extension of the thermal IR bright spiral arm. Alternatively, it is equally plausible that this feature is a weakly polarized but locally bright region of the inner disk wall. Astrometric monitoring of this feature over the next 2 years and emission line measurements could confirm its status as a protoplanet, rotating disk hot spot that is possibly a signpost of a protoplanet, or a stationary emission source from within the disk.

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The frequency of accretion disks around single stars: Chamaeleon I

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It is well known that stellar companions can influence the evolution of a protoplanetary disk. Nevertheless, previous disk surveys did not – and could not – consistently exclude binaries from their samples. We present a study dedicated to investigating the frequency of ongoing disk accretion around single stars in a star-forming region. We obtained near-infrared spectroscopy of 54 low-mass stars selected from a high-angular resolution survey in the 2–3 Myr-old ChamaeleonI region to determine the presence of Brackett-γ emission, taking the residual chance of undetected multiplicity into account, which we estimate to be on the order of 30%. The result is compared with previous surveys of the same feature in binary stars of the same region to provide a robust estimate of the difference between the accretor fractions of single stars and individual components of binary systems. We find Brγ emission among 39.5⁺¹⁴.⁰₋⁹.⁹ % of
single stars, which is a significantly higher fraction than for binary stars in Chamaeleon I. In particular, close binary systems with separations <100 AU show emission in only $6.5^{+16.5}_{-3.0}$% of the cases according to the same analysis. The emitter frequency of wider binaries appears consistent with the single star value. Interpreting Brγ emission as a sign of ongoing accretion and correcting for sensitivity bias, we infer an accretor fraction of single stars of $F_{acc} = 47.8^{+14.0}_{-9.9}$%. This is slightly higher but consistent with previous estimates that do not clearly exclude binaries from their samples. Through our robust and consistent analysis, we confirm that the fraction of young single stars harboring accretion disks is much larger than that of close binaries at the same age. Our findings have important implications for the timescales of disk evolution and planet formation.

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Hubble Tarantula Treasury Project. IV. The extinction law

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We report on the study of interstellar extinction across the Tarantula nebula (30 Doradus), in the Large Magellanic Cloud, using observations from the Hubble Tarantula Treasury Project in the 0.3 – 1.6μm range. The considerable and patchy extinction inside the nebula causes about 3 500 red clump stars to be scattered along the reddening vector in the colour–magnitude diagrams, thereby allowing an accurate determination of the reddening slope in all bands. The measured slope of the reddening vector is remarkably steeper in all bands than in the Galactic diffuse interstellar medium. At optical wavelengths, the larger ratio of total-to-selective extinction, namely $R_V = 4.5 \pm 0.2$, implies the presence of a grey component in the extinction law, due to a larger fraction of large grains. The extra large grains are most likely ices from supernova ejecta and will significantly alter the extinction properties of the region until they sublimate in $50 – 100$ Myr. We discuss the implications of this extinction law for the Tarantula nebula and in general for regions of massive star formation in galaxies. Our results suggest that fluxes of strongly star forming regions are likely to be underestimated by a factor of about 2 in the optical.

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Evidence of Short Timescale Flux Density Variations of UC H II regions in Sgr B2 Main and North

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We have recently published observations of significant flux density variations at 1.3 cm in H\textsc{ii} regions in the star forming regions Sgr B2 Main and North (De Pree et al. 2014). To further study these variations, we have made new 7 mm continuum and recombination line observations of Sgr B2 at the highest possible angular resolution of the Karl G. Jansky Very Large Array (VLA). We have observed Sgr B2 Main and North at 42.9 GHz and at 45.4 GHz in the BnA configuration (Main) and the A configuration (North). We compare these new data to archival VLA 7 mm continuum data of Sgr B2 Main observed in 2003 and Sgr B2 North observed in 2001. We find that one of the 41 known ultracompact and hypercompact H\textsc{ii} regions in Sgr B2 (K2-North) has decreased $\sim 27\%$ in flux density from 142$\pm$14 mJy to 103$\pm$10 mJy (2.3$\sigma$) between 2001 and 2012. A second source, F3c-Main has increased $\sim 30\%$ in flux density from 82$\pm$8 mJy to 107$\pm$11 mJy (1.8$\sigma$) between 2003 and 2012. F3c-Main was previously observed to increase in flux density at 1.3 cm over a longer time period between 1989 and 2012 (De Pree et al. 2014). An observation of decreasing flux density, such as that observed in K2-North, is particularly significant since such a change is not predicted by the classical hypothesis of steady expansion of H\textsc{ii} regions during massive star accretion. Our new observations at 7 mm, along with others in the literature, suggest that the formation of massive stars occurs through time-variable and violent accretion.

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On the effects of rotation in primordial star-forming clouds

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The thermodynamical evolution of gas during the collapse of the primordial star-forming cloud depends significantly on the initial degree of rotation. However, there is no clear understanding of how the initial rotation can affect the heating and cooling process and hence the temperature that leads to the fragmentation of the gas during Population III star formation. We report the results from three-dimensional, smoothed-particle hydrodynamics (SPH) simulations of a rotating self-gravitating primordial gas cloud with a modified version of the Gadget-2 code, in which the initial ratio of the rotational to the gravitational energy ($\beta_0$) is varied over two orders of magnitude. We find that despite the lack of any initial turbulence and magnetic fields in the clouds, the angular momentum distribution leads to the formation and build-up of a disk that fragments into several clumps. We further examine the behavior of the protostars that form in both idealized as well as more realistic minihalos from the cosmological simulations. The thermodynamical evolution and the fragmentation behavior of the cosmological minihalos are similar to that of the artificial cases, especially in those with a similar $\beta_0$-parameter. Protostars with a higher rotation support exhibit spiral-arm-like structures on several scales, and have lower accretion rates. These type of clouds tend to fragment more, while some of the protostars escape from the cluster with the possibility of surviving until the present day. They also take much longer to form compared to their slowly rotating counterparts. We conclude that the use of appropriate initial conditions of the gas in minihalos is a pivotal and decisive quantity to study the evolution and final fate of the primordial stars.

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Stellar feedback efficiencies: supernovae versus stellar winds
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Stellar winds and supernova (SN) explosions of massive stars ("stellar feedback") create bubbles in the interstellar medium (ISM) and insert newly produced heavy elements and kinetic energy into their surroundings, possibly driving turbulence. Most of this energy is thermalized and immediately removed from the ISM by radiative cooling. The rest is available for driving ISM dynamics. In this work we estimate the amount of feedback energy retained as kinetic energy when the bubble walls have decelerated to the sound speed of the ambient medium. We show that the feedback of the most massive star outweighs the feedback from less massive stars. For a giant molecular cloud (GMC) mass of \(10^5 M_\odot\) (as e.g. found in the Orion GMCs) and a star formation efficiency of 8\% the initial mass function predicts a most massive star of approximately 60 \(M_\odot\). For this stellar evolution model we test the dependence of the retained kinetic energy of the cold GMC gas on the inclusion of stellar winds. In our model winds insert 2.34 times the energy of a SN and create stellar wind bubbles serving as pressure reservoirs. We find that during the pressure driven phases of the bubble evolution radiative losses peak near the contact discontinuity (CD), and thus, the retained energy depends critically on the scales of the mixing processes across the CD. Taking into account the winds of massive stars increases the amount of kinetic energy deposited in the cold ISM from 0.1\% to a few percent of the feedback energy.

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Protostellar accretion traced with chemistry: Comparing synthetic C\textsuperscript{18}O maps of embedded protostars to real observations
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Context. Understanding how protostars accrete their mass is a central question of star formation. One aspect of this is to try and understand if the time evolution of accretion rates in deeply embedded objects is best characterised by a smooth decline from early to late stages, or by intermittent bursts of high accretion.

Aims. We create synthetic observations of deeply embedded protostars in a large numerical simulation of a molecular cloud, which are compared directly to real observations. The goal is to compare episodic accretion events in the simulation to observations, and to test the methodology used for analysing the observations.

Methods. Simple freeze-out and sublimation chemistry is added to the simulation, and synthetic C\textsuperscript{18}O line cubes are created for a large number of simulated protostars. The spatial extent of C\textsuperscript{18}O is measured for the simulated protostars, and compared directly to a sample of 16 deeply embedded protostars observed with the Submillimeter Array. If CO is distributed over a larger area than predicted based on the protostellar luminosity, it may indicate that the luminosity has been higher in the past, and that CO is still in the process of refreezing.

Results. Approximately 1\% of the protostars in the simulation show extended C\textsuperscript{18}O emission, as opposed to approximately 50\% in the observations, indicating that the magnitude and frequency of episodic accretion events in the simulation is too low relative to observations. The protostellar accretion rates in the simulation are primarily modulated by infall from the larger scales of the molecular cloud, and do not include any disk physics. The discrepancy
between simulation and observations is taken as support for the necessity of disks, even in deeply embedded objects, to produce episodic accretion events of sufficient frequency and amplitude.

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Spectroscopic and photometric analysis of the early-type spectroscopic binary HD 161853 in the centre of an H II region

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We study the O-type star HD 161853, which has been noted as a probable double-lined spectroscopic binary system. We secured high-resolution spectra of HD 161853 during the past nine years. We separated the two components in the system and measured their respective radial velocities for the first time. We confirm that HD 161853 is an \( \sim 1 \) Ma old binary system consisting of an O8 V star \((M_A, R_V \geq 22 M_\odot)\) and a B1–3 V star \((M_B, R_V \geq 7.2 M_\odot)\) at about 1.3 kpc. From the radial velocity curve, we measure an orbital period \( P = 2.66765 \pm 0.00001 \) d and an eccentricity \( e = 0.121 \pm 0.007 \). Its V-band light curve is constant within 0.014 mag and does not display eclipses, from which we impose a maximum orbital inclination \( i = 54^\circ \). HD 161853 is probably associated with an H II region and a poorly investigated very young open cluster. In addition, we detect a compact emission region at 50\arcsec to HD 161853 in 22\,\mu m-WISE and 24\,\mu m-Spitzer images, which may be identified as a dust wave piled up by the radiation pressure of the massive binary system.

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Investigating the origin and spectroscopic variability of the near-infrared HI lines in the Herbig star VV Ser

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The origin of the near-infrared (NIR) H\( \text{i} \) emission lines in young stellar objects are not yet understood. To probe it, we present multi-epoch LBT-LUCIFER spectroscopic observations of the Pa\( \delta \), Pa\( \beta \), and Br\( \gamma \) lines observed in the Herbig star VV Ser, along with VLTI-AMBER Br\( \gamma \) spectro-interferometric observations at medium resolution. Our spectroscopic observations show line profile variability in all the H\( \text{i} \) lines. The strongest variability is observed in the redshifted part of the line profiles. The Br\( \gamma \) spectro-interferometric observations indicate that the Br\( \gamma \) line emitting region is smaller than the continuum emitting region. To interpret our results, we employed radiative transfer models with three different flow configurations: magnetospheric accretion, a magneto-centrifugally driven disc wind, and a schematic bipolar outflow. Our models suggest that the H\( \text{i} \) line emission in VV Ser is dominated by the contribution
of an extended wind, perhaps a bipolar outflow. Although the exact physical process for producing such outflow is not known, this model is capable of reproducing the averaged single-peaked line profiles of the H\textsc{i} lines. Additionally, the observed visibilities, differential and closure phases are best reproduced when a wind is considered. Nevertheless, the complex line profiles and variability could be explained by changes in the relative contribution of the magnetosphere and/or winds to the line emission. This might indicate that the NIR H\textsc{i} lines are formed in a complex inner disc region where inflow and outflow components might coexist. Furthermore, the contribution of each of these mechanisms to the line appears time variable, suggesting a non-steady accretion/ejection flow.

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Massive star formation by accretion I. Disc accretion

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Massive stars likely form by accretion and the evolutionary track of an accreting forming star corresponds to what is called the birthline in the HR diagram. The shape of this birthline is quite sensitive to the evolution of the entropy in the accreting star. We first study the reasons why some birthlines published in past years present different behaviours for a given accretion rate. We then revisit the question of the accretion rate, which allows us to understand the distribution of the observed pre-main-sequence (pre-MS) stars in the Hertzsprung-Russell (HR) diagram. Finally, we identify the conditions needed to obtain a large inflation of the star along its pre-MS evolution that may push the birthline towards the Hayashi line in the upper part of the HR diagram. We present new pre-MS models including accretion at various rates and for different initial structures of the accreting core. From the observed upper envelope of pre-MS stars in the HR diagram, we deduce the accretion law that best matches the accretion history of most of the intermediate-mass stars. In the case of cold disc accretion, the existence of a significant swelling during the accretion phase, which leads to radii \( \gtrsim 100 \) \( R_\odot \) and brings the star back to the red part of the HR diagram, depends sensitively on the initial conditions. For an accretion rate of \( 10^{-3} \) \( M_\odot \) yr\(^{-1} \), only models starting from a core with a significant radiative region evolve back to the red part of the HR diagram. We also obtain that, in order to reproduce the observed upper envelope of pre-MS stars in the HR diagram with an accretion law deduced from the observed mass outflows in ultra-compact H\textsc{ii} regions, the mass effectively accreted onto the star with respect to the total in falling matter decreases when the mass of the star increases.

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Viscous Instability Triggered by Layered Accretion in Protoplanetary Disks

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Layered accretion is one of the inevitable ingredients in protoplanetary disks when disk turbulence is excited by magnetorotational instabilities (MRIs). In the accretion, disk surfaces where MRIs fully operate have a high value of disk accretion rate (\( \dot{M} \)), while the disk midplane where MRIs are generally quenched ends up with a low value of \( \dot{M} \). Significant progress on understanding MRIs has recently been made by a number of dedicated MHD simulations, which requires improvement of the classical treatment of \( \alpha \) in 1D disk models. To this end, we obtain a new expression of \( \alpha \) by utilizing an empirical formula that is derived from recent MHD simulations of stratified disks with Ohmic diffusion. It is interesting that this new formulation can be regarded as a general extension of the classical \( \alpha \). Armed
with the new $\alpha$, we perform a linear stability analysis of protoplanetary disks that undergo layered accretion, and find that a viscous instability can occur around the outer edge of dead zones. Disks become stable in using the classical $\alpha$. We identify that the difference arises from $\Sigma$-dependence of $\dot{M}$; whereas $\Sigma$ is uniquely determined for a given value of $\dot{M}$ in the classical approach, the new approach leads to $\dot{M}$ that is a multi-valued function of $\Sigma$. We confirm our finding both by exploring a parameter space as well as by performing the 1D, viscous evolution of disks. We finally discuss other non-ideal MHD effects that are not included in our analysis, but may affect our results.

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Chondrule Formation via Impact Jetting Triggered by Planetary Accretion
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Chondrules are one of the most primitive elements that can serve as a fundamental clue as to the origin of our Solar system. We investigate a formation scenario of chondrules that involves planetesimal collisions and the resultant impact jetting. Planetesimal collisions are the main agent to regulate planetary accretion that corresponds to the formation of terrestrial planets and cores of gas giants. The key component of this scenario is that ejected materials can melt when the impact velocity between colliding planetesimals exceeds about 2.5 km s$^{-1}$. The previous simulations show that the process is efficient enough to reproduce the primordial abundance of chondrules. We examine this scenario carefully by performing semi-analytical calculations that are developed based on the results of direct N-body simulations. As found by the previous work, we confirm that planetesimal collisions that occur during planetary accretion can play an important role in forming chondrules. This arises because protoplanet–planetesimal collisions can achieve the impact velocity of about 2.5 km s$^{-1}$ or higher, as protoplanets approach the isolation mass ($M_{P,iso}$). Assuming that the ejected mass is a fraction ($F_{ch}$) of colliding planetesimals' mass, we show that the resultant abundance of chondrules is formulated well by $F_{ch}M_{P,iso}$, as long as the formation of protoplanets is completed within a given disk lifetime. We perform a parameter study and examine how the abundance of chondrules and their formation timing change. We find that the impact jetting scenario generally works reasonably well for a certain range of parameters, while more dedicated work would be needed to include other physical processes that are neglected in this work and to examine their effects on chondrule formation.

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A New Mechanism for Chondrule Formation: Radiative Heating by Hot Planetesimals
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We propose that chondrules are formed by radiative heating of pre-existing dust clumps during close fly-bys of planetesimals with incandescent lava at their surfaces. We show that the required temperatures and cooling rates are easily achieved in this scenario and discuss how it is consistent with bulk aspects of chondritic meteorites, including complementarity and the co-mingling of FeO-poor and FeO-rich chondrules.

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Sgr B2(N): A bipolar outflow and rotating hot core revealed by ALMA

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We present the results of SiO (2−1) and SO2 (124,8 − 133,11) line observations of Sgr B2(N) made with the Atacama Large Millimeter/submillimeter Array (ALMA) at an angular resolution of ~2 arcsec. Our analysis of the SiO and SO2 line emission reveals a bipolar molecular outflow in an east-west direction whose driving source is located at K2. In addition, SO2 line core shows a north-south velocity gradient most probably indicating a hot core of molecular gas rotating around K2. Fractional abundances of SO2 and SiO (X(SO2) and X(SiO), respectively) in the outflowing molecular gas are derived from comparisons with the C18O emission. Assuming an excitation temperature of 100 ± 50 K, we calculate X(SO2) = 2.3+2.6−0.4×10−8 and X(SiO) = 1.2+0.1−0.1×10−9. The outflow from Sgr B2(N) K2 is characterized as a young (5×10^3 yr) and massive (∼2000 M⊙), but moderately collimated (∼60°) outflow. We also report a possible detection of the SiO (v = 2, J = 2 − 1) maser emission from the position of K2. If confirmed, it would make Sgr B2(N) the 4th star forming region associated with SiO masers.

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Inside-Out Planet Formation. III. Planet-disk interaction at the dead zone inner boundary

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The Kepler mission has discovered more than 4000 exoplanet candidates. Many of them are in systems with tightly packed inner planets (STIPs). Inside-Out Planet Formation (IOPF) (Chatterjee & Tan 2014) has been proposed as a scenario to explain these systems. It involves sequential in situ planet formation at the local pressure maximum of a retreating dead zone inner boundary (DZIB). Pebbles accumulate at this pressure trap, which builds up a pebble ring, and then a planet. The planet is expected to grow in mass until it opens a gap, which helps to both truncate pebble accretion and also induce DZIB retreat that sets the location of formation of the next planet. This simple scenario may be modified if the planet undergoes significant migration from its formation location. Thus planet-disk interactions play a crucial role in the IOPF scenario. Here we present numerical simulations that first assess the degree of migration for planets of various masses that are forming at the DZIB of an active accretion disk, where the effective viscosity is undergoing a rapid increase in the radially inward direction. We find that torques exerted on the planet by the disk tend to trap the planet at a location very close to the initial pressure maximum where it formed. We then study gap opening by these planets to assess at what mass a significant gap is created. Finally we present a simple model for DZIB retreat due to penetration of X-rays from the star to the disk midplane. Overall, these simulations help to quantify both the mass scale of first, “Vulcan,” planet formation and the orbital separation to the location of second planet formation.

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First Scattered-Light Image of the Debris Disk around HD 131835 with the Gemini Planet Imager

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We present the first scattered-light image of the debris disk around HD 131835 in H band using the Gemini Planet Imager. HD 131835 is a ~15 Myr old A2IV star at a distance of ~120 pc in the Sco-Cen OB association. We detect the disk only in polarized light and place an upper limit on the peak total intensity. No point sources resembling exoplanets were identified. Compared to its mid-infrared thermal emission, the disk in scattered light shows similar orientation but different morphology. The scattered-light disk extends from ~75 to ~210 AU in the disk plane with roughly flat surface density. Our Monte Carlo radiative transfer model can well describe the observations with a model disk composed of a mixture of silicates and amorphous carbon. In addition to the obvious brightness asymmetry due to stronger forward scattering, we discover a weak brightness asymmetry along the major axis with the northeast side being 1.3 times brighter than the southwest side at a 3σ level.

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Photometric variability of 14 PMS stars in the NGC 7000/IC 5070 complex

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New photometric data from CCD multicolour BVRI observations of 14 pre-main sequence stars during the period from 2013 April to 2015 September are presented. The studied objects are located in the field of ‘Gulf of Mexico’ in the NGC 7000/IC 5070 star-forming complex. The stars from our study exhibit different types of photometric variability in all optical passbands. Using our long-term observations and data published by other authors, we tried to define the reasons for the observed brightness variations. On the basis of our new data previously unknown periodicity in the light curve of the star LkHα 189 (2.45 days) was registered.

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Large-scale CO ($J=4$–3) Mapping toward the Orion-A Giant Molecular Cloud

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We have mapped the Orion-A Giant Molecular Cloud in the CO ($J=4$–3) line with the Tsukuba 30-cm submillimeter telescope. The map covered a 7.125 deg$^2$ area with a 9$^\prime$ resolution, including main components of the cloud such as Orion Nebula, OMC-2/3, and L1641-N. The most intense emission was detected toward the Orion KL region. The integrated intensity ratio between CO ($J=4$–3) and CO ($J=1$–0) was derived using data from the Columbia-Univ. de Chile CO survey, which was carried out with a comparable angular resolution. The ratio was $r_{4–3/1–0} \sim 0.2$ in the southern region of the cloud and 0.4–0.8 at star forming regions. We found a trend that the ratio shows higher value at edges of the cloud. In particular the ratio at the north-eastern edge of the cloud at ($l$, $b$) = (208$^\circ$375, $-19^\circ$0) shows the specific highest value of 1.1. The physical condition of the molecular gas in the cloud was estimated by non-LTE calculation. The result indicates that the kinetic temperature has a gradient from north ($T_{\text{kin}} = 80$ K) to south (20 K). The estimation shows that the gas associated with the edge of the cloud is warm ($T_{\text{kin}} \sim 60$ K), dense ($n_{\text{H}_2} \sim 10^4$ cm$^{-3}$), and optically thin, which may be explained by heating and sweeping of interstellar materials from OB clusters.

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External Photoevaporation of the Solar Nebula II. Effects on Disk Structure and Evolution with Non-Uniform Turbulent Viscosity due to the Magnetorotational Instability

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The structure and evolution of protoplanetary disks, especially the radial flows of gas through them, are sensitive to a number of factors. One that has been considered only occasionally in the literature is external photoevaporation by far-ultraviolet (FUV) radiation from nearby, massive stars, despite the fact that nearly half of disks will experience photoevaporation. Another effect apparently not considered in the literature is a spatially and temporally varying value of $\alpha$ in the disk [where the turbulent viscosity $\nu$ is $\alpha$ times the sound speed $C$ times the disk scale height $H$].

Here we use the formulation of Bai & Stone (2011) to relate $\alpha$ to the ionization fraction in the disk, assuming turbulent
transport of angular momentum is due to the magnetorotational instability. Disk evolution is most sensitive to the surface area of dust. We find that typically $\alpha < 10^{-5}$ in the inner disk ($< 2$ AU), rising to $\sim 10^{-3}$ beyond 20 AU. This drastically alters the structure of the disk and the flow of mass through it: while the outer disk rapidly viscously spreads, the inner disk hardly evolves; this leads to a steep surface density profile ($\Sigma \propto r^{-\langle p \rangle}$ with $\langle p \rangle \approx 2 - 5$ in the 5-30 AU region) that is made steeper by external photoevaporation. We also find that the combination of variable $\alpha$ and external photoevaporation eventually causes gas as close as 3 AU, previously accreting inward, to be drawn outward to the photoevaporated outer edge of the disk. These effects have drastic consequences for planet formation and volatile transport in protoplanetary disks.

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The JCMT Gould Belt Survey: A First Look at Dense Cores in Orion B

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We present a first look at the SCUBA-2 observations of three sub-regions of the Orion B molecular cloud: LDN 1622, NGC 2023/2024, and NGC 2068/2071, from the JCMT Gould Belt Legacy Survey. We identify 29, 564, and 322 dense cores in L1622, NGC 2023/2024, and NGC 2068/2071 respectively, using the SCUBA-2 850 µm map, and present their basic properties, including their peak fluxes, total fluxes, and sizes, and an estimate of the corresponding 450 µm peak fluxes and total fluxes, using the FellWalker source extraction algorithm. Assuming a constant temperature of 20 K, the starless dense cores have a mass function similar to that found in previous dense core analyses, with a Salpeter-like slope at the high-mass end. The majority of cores appear stable to gravitational collapse when considering only thermal pressure; indeed, most of the cores which have masses above the thermal Jeans mass are already associated with at least one protostar. At higher cloud column densities, above $1 - 2 \times 10^{23}$ cm$^{-2}$, most of the mass is found within dense cores, while at lower cloud column densities, below $1 \times 10^{23}$ cm$^{-2}$, this fraction drops to 10% or lower. Overall, the fraction of dense cores associated with a protostar is quite small (< 8%), but becomes larger for the densest and most centrally concentrated cores. NGC 2023/2024 and NGC 2068/2071 appear to be on the path to forming a significant number of stars in the future, while L1622 has little additional mass in dense cores to form many new stars.

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A panoptic model for planetesimal formation and pebble delivery

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The journey from dust particle to planetesimal involves physical processes acting on scales ranging from micrometers (the sticking and restructuring of aggregates) to hundreds of astronomical units (the size of the turbulent protoplanetary nebula). Considering these processes simultaneously is essential when studying planetesimal formation. The goal of this work is to quantify where and when planetesimal formation can occur as the result of porous coagulation of icy grains and to understand how the process is influenced by the properties of the protoplanetary disk. We develop a novel, global, semi-analytical model for the evolution of the mass-dominating dust particles in a turbulent protoplanetary disk that takes into account the evolution of the dust surface density while preserving the essential characteristics of the porous coagulation process. This panoptic model is used to study the growth from submicron to planetesimal sizes in disks around Sun-like stars. For highly porous ices, unaffected by collisional fragmentation and erosion, rapid growth to planetesimal sizes is possible in a zone stretching out to $\sim 10$ AU for massive disks. When porous coagulation is limited by erosive collisions, the formation of planetesimals through direct coagulation is not possible, but the creation of a large population of aggregates with Stokes numbers close to unity might trigger the streaming instability (SI). However, we find that reaching conditions necessary for SI is difficult and limited to dust-rich disks, (very) cold disks, or disks with weak turbulence. Behind the snow-line, porosity-driven aggregation of icy grains results in rapid ($\sim 10^4$ yr) formation of planetesimals. If erosive collisions prevent this, SI might be triggered for specific disk conditions. The numerical approach introduced in this work is ideally suited for studying planetesimal formation and pebble delivery simultaneously and will help build a coherent picture of the start of the planet formation process.

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Variable stars in young open star cluster NGC 7380

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We present time series photometry of 57 variable stars in the cluster region NGC 7380. The association of these variable stars to the cluster NGC 7380 has been established on the basis of two colour diagrams and colour-magnitude diagrams. Seventeen stars are found to be main-sequence variables, which are mainly B type stars and are classified as slowly pulsating B stars, δ Cep or δ Scuti stars. Some of them may belong to new class variables as discussed by Mowlavi et al. (2013) and Lata et al. (2014). Present sample also contains 14 pre-main-sequence stars, whose ages and masses are found to be mostly ∼5 Myr and range 0.60 ∼ M/M⊙ < 2.30 and hence should be T-Tauri stars. About half of the weak line T-Tauri stars are found to be fast rotators with a period of ∼2 days as compared to the classical T-Tauri stars. Some of the variables belong to the field star population.

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each source obtained from two-dimensional fits to the SMA C$^{18}$O emission are found to be perpendicular to within 20° of the outflow directions as revealed by $^{12}$CO ($J=2–1$). We have observed that Sources B and NW with multiplicity have higher densities than Source A without multiplicity. This suggests that thermal Jeans fragmentation can be relevant in the fragmentation process. However, we have not observed a difference in the ratio between rotational and gravitational energy between sources with and without multiplicity. We also have not observed a trend between non-thermal velocity dispersions and the level of fragmentation. Our study has provided the first direct and comprehensive comparison between multiplicity and core properties in low-mass protostars, although based on small number statistics.

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Sejong open cluster survey (SOS) - V. The active star forming region Sh 2-255 – 257

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There is much observational evidence that active star formation is taking place in the HII regions Sh 2-255 – 257. We present a photometric study of this star forming region (SFR) using imaging data obtained in passbands from the optical to the mid-infrared in order to study the star formation process. A total of 218 members were identified using various selection criteria based on their observational properties. The SFR is reddened by at least $E(B-V) = 0.8$ mag, and the reddening law toward the region is normal ($R_V = 3.1$). From the zero-age main sequence fitting method it is confirmed that the SFR is 2.1±0.3 kpc from the Sun. The median age of the identified members is estimated to be about 1.3 Myr from comparison of the Hertzsprung-Russell diagram (HRD) with stellar evolutionary models. The initial mass function (IMF) is derived from the HRD and the near-infrared ($J, H, K$) color-magnitude diagram. The slope of the IMF is about $\Gamma = -1.6 \pm 0.1$, which is slightly steeper than that of the Salpeter/Kroupa IMF. It implies that low-mass star formation is dominant in the SFR. The sum of the masses of all the identified members provides the lower limit of the cluster mass ($169 M_\odot$). We also analyzed the spectral energy distribution (SED) of pre-main sequence stars using the SED fitting tool of Robitaille et al. and confirm that there is a significant discrepancy between stellar mass and age obtained from two different methods based on the SED fitting tool and the HRD.

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Planck cold clumps in the $\lambda$ Orionis complex: I. Discovery of an extremely young Class 0 protostellar object and a proto-brown dwarf candidate in a bright rimmed clump PGCC G192.32–11.88

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We are performing a series of observations with ground-based telescopes toward Planck Galactic cold clumps (PGCCs) in the λ Orionis complex in order to systematically investigate the effects of stellar feedback. In the particular case of PGCC G192.32−11.88, we discovered an extremely young Class 0 protostellar object (G192N) and a proto-brown dwarf candidate (G192S). G192N and G192S are located in a gravitationally bound bright-rimmed clump. The velocity and temperature gradients seen in line emission of CO isotopologues indicate that PGCC G192.32−11.88 is externally heated and compressed. G192N probably has the lowest bolometric luminosity (∼0.8 L⊙) and accretion rate (6.3 × 10⁻⁷ M⊙ yr⁻¹) when compared with other young Class 0 sources (e.g. PACS Bright Red sources (PBRs)) in the Orion complex. It has slightly larger internal luminosity (0.21±0.01 L⊙) and outflow velocity (∼14 km s⁻¹) than the predictions of first hydrostatic cores (FHSCs). G192N might be among the youngest Class 0 sources, which are slightly more evolved than a FHSC. Considering its low internal luminosity (0.08±0.01 L⊙) and accretion rate (2.8 × 10⁻⁸ M⊙ yr⁻¹), G192S is an ideal proto-brown dwarf candidate. The star formation efficiency (∼0.3%–0.4%) and core formation efficiency (∼1%) in PGCC G192.32−11.88 are significantly smaller than in other giant molecular clouds or filaments, indicating that the star formation therein is greatly suppressed due to stellar feedback.

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Vertical Structure of Magnetized Accretion Disks around Young Stars

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We model the vertical structure of magnetized accretion disks subject to viscous and resistive heating, and irradiation by the central star. We apply our formalism to the radial structure of magnetized accretion disks threaded by a poloidal magnetic field dragged during the process of star formation developed by Shu and coworkers. We consider disks around low mass protostars, T Tauri, and FU Orionis stars. We consider two levels of disk magnetization, \( \lambda_{magnetized disks} \), and \( \lambda = 12 \) (weakly magnetized disks). The rotation rates of strongly magnetized disks have large deviations from Keplerian rotation. In these models, resistive heating dominates the thermal structure for the FU Ori disk. The T Tauri disk is very thin and cold because it is strongly compressed by magnetic pressure; it may be too thin compared with observations. Instead, in the weakly magnetized disks, rotation velocities are close to Keplerian, and resistive heating is always less than 7% of the viscous heating. In these models, the T Tauri disk has a larger aspect ratio, consistent with that inferred from observations. All the disks have spatially extended hot atmospheres where the irradiation flux is absorbed, although most of the mass (~ 90 – 95 %) is in the disk midplane. With the advent of ALMA one expects direct measurements of magnetic fields and their morphology at disk scales. It will then be possible to determine the mass-to-flux ratio of magnetized accretion disks around young stars, an essential parameter for their structure and evolution. Our models contribute to the understanding of the vertical structure and emission of these disks.

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An eclipsing double-line spectroscopic binary at the stellar/substellar boundary in the Upper Scorpius OB association

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We aim at constraining evolutionary models at low mass and young ages by identifying interesting transiting system members of the nearest OB association to the Sun, Upper Scorpius, targeted by the Kepler mission. We produced light curves for M dwarf members of the USco region surveyed during the second campaign of the Kepler K2 mission. We identified ‘by eye’ a transiting system, UScoJ16 1630.68 (=EPIC203710387) with a combined spectral type of M5.25 whose photometric, astrometric, and spectroscopic properties make it a member of USco. We conducted an extensive photometric and spectroscopic follow-up of this transiting system with a suite of telescopes and instruments to characterise the properties of each component of the system.

We calculated a transit duration of about 2.42 hours occurring every 2.88 days with a slight difference in transit depth and phase between the two components. We estimated a mass ratio of 0.922 \( \pm 0.005 \) for the primary and secondary, respectively. We derived masses of 0.091 \( \pm 0.005 \) \( M_\odot \) and 0.084 \( \pm 0.004 \) \( M_\odot \), radii of 0.388 \( \pm 0.008 \) \( R_\odot \) and 0.380 \( \pm 0.008 \) \( R_\odot \), luminosities of \( \log(L/L_\odot) = -2.020^{+0.199}_{-0.121} \) dex and \( -2.032^{+0.099}_{-0.121} \) dex, and effective temperatures of 2901 \( ^{+199}_{-172} \) K and 2908 \( ^{+199}_{-172} \) K for the primary and secondary, respectively.

We present a complete photometric and radial velocity characterisation of the least massive double-line eclipsing binary system in the young USco association with two components close to the stellar/substellar limit. This system fills in a gap between the least massive eclipsing binaries in the low-mass and substellar regimes at young ages and represents
On shocks driven by high-mass planets in radiatively inefficient disks. II. Three-dimensional global disk simulations

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Recent high-resolution, near-infrared images of protoplanetary disks have shown that these disks often present spiral features. Spiral arms are among the structures predicted decades ago by numerical simulations of disk-planet interaction and thus it is tempting to suspect that planetary perturbers are responsible for the observed signatures. However, such interpretation is not free of problems. The spirals are found to have large pitch angles, and in at least one case (HD 100546) the spiral feature appears effectively unpolarized, which implies thermal emission of the order of $1000K$ ($465\pm40K$ at closer inspection). We have recently shown in two-dimensional models that shock dissipation in the supersonic wake of high-mass planets can lead to significant heating if the disk is sufficiently adiabatic. In this paper we extend this analysis to three dimensions in thermodynamically evolving disks. We use the Pencil Code in spherical coordinates for our models, with a prescription for thermal cooling based on the optical depth of the local vertical gas column. We use a 5 $M_J$ planet, and show that shocks in the region around the planet where the Lindblad resonances occur heat the gas to substantially higher temperatures than the ambient disk gas at that radius. The gas is accelerated vertically away from the midplane by the shocks to form shock bores, and the gas falling back toward the midplane breaks up into a turbulent surf near the Lindblad resonances. This turbulence, although localized, has high $\alpha$ values, reaching 0.05 in the inner Lindblad resonance, and 0.1 in the outer one. We also find evidence that the disk regions heated up by the planetary shocks eventually becomes superadiabatic, generating convection far from the planet’s orbit.

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First light of the VLT planet finder SPHERE. II. The physical properties and the architecture of the young systems PZ Tel and HD 1160 revisited

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Context. The young systems PZ Tel and HD 1160, hosting known low-mass companions, were observed during the commissioning of the new planet finder SPHERE with several imaging and spectroscopic modes.

Aims. We aim to refine the physical properties and architecture of both systems.

Methods. We use SPHERE commissioning data and REM observations, as well as literature and unpublished data from VLT/SINFONI, VLT/NaCo, Gemini/NICI, and Keck/NIRC2.

Results. We derive new photometry and confirm the nearly daily photometric variability of PZ Tel A. Using literature data spanning 38 yr, we show that the star also exhibits a long-term variability trend. The 0.63–3.8 μm SED of PZ Tel B allows us to revise its properties: spectral type M7±1, Teff = 2700±100 K, log(g) < 4.5 dex, log(L/L⊙) = −2.51±0.10 dex, and mass 38–72 MJ. The 1–3.8 μm SED of HD 1160 B suggests a massive brown dwarf or a low-mass star with spectral type M5.5–7.0, Teff = 3000±100 K, [M/H] = −0.5–0.0 dex, log(L/L⊙) = −2.81±0.10 dex, and mass 39–168 MJ. We confirm the deceleration and high eccentricity (e > 0.66) of PZ Tel B. For e < 0.9, the inclination, longitude of the ascending node, and time of periastron passage are well constrained. The system is seen close to an edge-on geometry. We reject other brown dwarf candidates outside 0′′.25 for both systems, and massive giant planets (>4 MJ) outside 0′′.5 for the PZ Tel system. We also show that K1 – K2 color can be used with YJH low-resolution spectra to identify young L-type companions, provided high photometric accuracy (<0.05 mag) is achieved.
Conclusions. SPHERE opens new horizons in the study of young brown dwarfs and giant exoplanets thanks to high-contrast imaging capabilities at optical and near-infrared wavelengths, as well as high signal-to-noise spectroscopy in the near-infrared from low ($R \sim 30-50$) to medium resolutions ($R \sim 350$).

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Star cluster formation with stellar feedback and large-scale inflow

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During star cluster formation, ongoing mass accretion is resisted by stellar feedback in the form of protostellar outflows from the low mass stars and photo-ionization and radiation pressure feedback from the massive stars. We model the evolution of cluster-forming regions during a phase in which both accretion and feedback are present, and use these models to investigate how star cluster formation might terminate. Protostellar outflows are the strongest form of feedback in low-mass regions, but these cannot stop cluster formation if matter continues to flow in. In more massive clusters, radiation pressure and photo-ionization rapidly clear the cluster-forming gas when its column density is too small. We assess the rates of dynamical mass ejection and of evaporation, while accounting for the important effect of dust opacity on photo-ionization. Our models are consistent with the census of protostellar outflows in NGC 1333 and Serpens South, and with the dust temperatures observed in regions of massive star formation. Comparing observations of massive cluster-forming regions against our model parameter space, and against our expectations for accretion-driven evolution, we infer that massive-star feedback is a likely cause of gas disruption in regions with velocity dispersions less than a few kilometers per second, but that more massive and more turbulent regions are too strongly bound for stellar feedback to be disruptive.

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A nebular analysis of the central Orion Nebula with MUSE


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A nebular analysis of the central Orion Nebula and its main structures is presented. We exploit MUSE integral field observations in the wavelength range 4595–9366 Å to produce the first O, S and N ionic and total abundance maps of a region spanning $6' \times 5'$ with a spatial resolution of $0''.2$. We use the S23 ($= ([\text{SII}]\lambda 6717,31+[\text{SIII}]\lambda 9068)/H_\beta$) parameter, together with $[\text{OII}]/[\text{OIII}]$ as an indicator of the degree of ionisation, to distinguish between the various small-scale structures. The only Orion Bullet covered by MUSE is HH 201, which shows a double component in the $[\text{FeII}]\lambda 8617$ line throughout indicating an expansion, and we discuss a scenario in which this object is undergoing a disruptive event. We separate the proplyds located south of the Bright Bar into four categories depending on their S23 values, propose the utility of the S23 parameter as an indicator of the shock-contribution to the excitation of line-emitting atoms, and show that the MUSE data is able to identify the proplyds associated with disks and microjets. We compute the second order structure function for the Hα, $[\text{OIII}]\lambda 5007$, $[\text{SII}]\lambda 6731$ and $[\text{OI}]\lambda 6300$ emission lines to analyse the turbulent velocity field of the region covered with MUSE. We find that the spectral and spatial resolution of MUSE is not able to faithfully reproduce the structure functions of previous works.

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The Spitzer Space Telescope Survey of the Orion A and B Molecular Clouds II: the Spatial Distribution and Demographics of Dusty Young Stellar Objects


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We analyze the spatial distribution of dusty young stellar objects (YSOs) identified in the Spitzer Survey of the Orion Molecular clouds, augmenting these data with Chandra X-ray observations to correct for incompleteness in dense clustered regions. We also devise a scheme to correct for spatially varying incompleteness when X-ray data are not available. The local surface densities of the YSOs range from 1 pc$^{-2}$ to over 10,000 pc$^{-2}$, with protostars tending to be in higher density regions. This range of densities is similar to other surveyed molecular clouds with clusters, but broader than clouds without clusters. By identifying clusters and groups as continuous regions with surface densities \( \geq 10 \) pc$^{-2}$, we find that 59% of the YSOs are in the largest cluster, the Orion Nebular Cluster (ONC), while 13% of the YSOs are found in a distributed population. A lower fraction of protostars in the distributed population is evidence that it is somewhat older than the groups and clusters. An examination of the structural properties of the clusters and groups show that the peak surface densities of the clusters increase approximately linearly with the number of members. Furthermore, all clusters with more than 70 members exhibit asymmetric and/or highly elongated structures. The ONC becomes azimuthally symmetric in the inner 0.1 pc, suggesting that the cluster is only \( \sim 2 \) Myr in age. We find the star formation efficiency (SFE) of the Orion B cloud is unusually low, and that the SFEs of individual groups and clusters are an order of magnitude higher than those of the clouds. Finally, we discuss the relationship between the young low mass stars in the Orion clouds and the Orion OB 1 association, and we determine upper limits to the fraction of disks that may be affected by UV radiation from OB stars or by dynamical interactions in dense, clustered regions.

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Fossilized condensation lines in the Solar System protoplanetary disk


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The terrestrial planets and the asteroids dominant in the inner asteroid belt are water poor. However, in the pro-
to planetary disk the temperature should have decreased below water condensation level well before the disk was photoevaporated. Thus, the global water depletion of the inner Solar System is puzzling. We show that, even if the inner disk becomes cold, there cannot be direct condensation of water. This is because the snowline moves towards the Sun more slowly than the gas itself. The appearance of ice in a range of heliocentric distances swept by the snowline can only be due to the radial drift of icy particles from the outer disk. However, if a sufficiently massive planet is present, the radial drift of particles is interrupted, because the disk acquires a superKeplerian rotation just outside of the planetary orbit. From this result, we propose that the precursor of Jupiter achieved about 20 Earth masses when the snowline was still around 3 AU. This effectively fossilized the snowline at that location. Although cooling, the disk inside of the Jovian orbit remained ice-depleted because the flow of icy particles from the outer system was intercepted by the planet. This scenario predicts that planetary systems without giant planets should be much more rich in water in their inner regions than our system. We also show that the inner edge of the planetesimal disk at 0.7AU, required in terrestrial planet formation models to explain the small mass of Mercury and the absence of planets inside of its orbit, could be due to the silicate condensation line, fossilized at the end of the phase of streaming instability that generated the planetesimal seeds. Thus, when the disk cooled, silicate particles started to drift inwards of 0.7AU without being sublimated, but they could not be accreted by any pre-existing planetesimals.

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Nested shells reveal the rejuvenation of the Orion-Eridanus superbubble
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The Orion-Eridanus superbubble is the prototypical superbubble due to its proximity and evolutionary state. Here, we provide a synthesis of recent observational data from WISE and Planck with archival data, allowing to draw a new and more complete picture on the history and evolution of the Orion-Eridanus region. We discuss the general morphological structures and observational characteristics of the superbubble, and derive quantitative properties of the gas and dust inside Barnard’s Loop. We reveal that Barnard’s Loop is a complete bubble structure which, together with the Λ Ori region and other smaller-scale bubbles, expands within the Orion-Eridanus superbubble. We argue that the Orion-Eridanus superbubble is larger and more complex than previously thought, and that it can be viewed as a series of nested shells, superimposed along the line of sight. During the lifetime of the superbubble, HII region champagne flows and thermal evaporation of embedded clouds continuously mass-load the superbubble interior, while winds or supernovae from the Orion OB association rejuvenate the superbubble by sweeping up the material from the interior cavities in an episodic fashion, possibly triggering the formation of new stars that form shells of their own. The steady supply of material into the superbubble cavity implies that dust processing from interior supernova remnants is more efficient than previously thought. The cycle of mass-loading, interior cleansing, and star formation repeats until the molecular reservoir is depleted or the clouds have been disrupted. While the nested shells come and go, the superbubble remains for tens of millions of years.

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Did the Solar System form in a sequential triggered star formation event?
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The presence and abundance of the short-lived radioisotopes (SLRs) 26Al and 60Fe during the formation of the Solar System is difficult to explain unless the Sun formed in the vicinity of one or more massive star(s) that exploded as
supernovae. Two different scenarios have been proposed to explain the delivery of SLRs to the protosolar nebula: (i) direct pollution of the protosolar disc by supernova ejecta and (ii) the formation of the Sun in a sequential star formation event in which supernovae shockwaves trigger further star formation which is enriched in SLRs. The sequentially triggered model has been suggested as being more astrophysically likely than the direct pollution scenario. In this paper we investigate this claim by analysing a combination of N-body and SPH simulations of star formation. We find that sequential star formation would result in large age spreads (or even bi-modal age distributions for spatially coincident events) due to the dynamical relaxation of the first star-formation event(s). Secondly, we discuss the probability of triggering spatially and temporally discrete populations of stars and find this to be only possible in very contrived situations. Taken together, these results suggest that the formation of the Solar System in a triggered star formation event is as improbable, if not more so, than the direct pollution of the protosolar disc by a supernova.

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The far-infrared behaviour of Herbig Ae/Be discs: Herschel PACS photometry

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Herbig Ae/Be objects are pre-main sequence stars surrounded by gas- and dust-rich circumstellar discs. These objects are in the throes of star and planet formation, and their characterisation informs us of the processes and outcomes of planet formation processes around intermediate mass stars. Here we analyse the spectral energy distributions of disc host stars observed by the Herschel Open Time Key Programme ‘Gas in Protoplanetary Systems’. We present Herschel/PACS far-infrared imaging observations of 22 Herbig Ae/Bes and 5 debris discs, combined with ancillary photometry spanning ultraviolet to sub-millimetre wavelengths. From these measurements we determine the diagnostics of disc evolution, along with the total excess, in three regimes spanning near-, mid-, and far-infrared wavelengths. Using appropriate statistical tests, these diagnostics are examined for correlations. We find that the far-infrared flux, where the disc becomes optically thin, is correlated with the millimetre flux, which provides a measure of the total dust mass. The ratio of far-infrared to sub-millimetre flux is found to be greater for targets with discs that are brighter at millimetre wavelengths and that have steeper sub-millimetre slopes. Furthermore, discs with flared geometry have, on average, larger excesses than flat geometry discs. Finally, we estimate the extents of these discs (or provide upper limits) from the observations.

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A new free-floating planet in the Upper Scorpius association

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We report on a deep photometric survey covering an area of 1.17 deg2 in the young Upper Scorpius stellar association using VIMOS I\text{z} and UKIDSS Z\text{JHK} data taking several years apart. The search for the least massive population of
Upper Scorpius (∼5–10 Myr, 145 pc) is performed on the basis of various optical and infrared color-color and color-magnitude diagrams, including WISE photometry, in the magnitude interval $J = 14.5–19$ mag (completeness), which corresponds to substellar masses from 0.028 through 0.004 $M_\odot$ at the age and distance of Upper Scorpius. We also present the proper motion analysis of the photometric candidates, finding that two objects successfully pass all photometric and astrometric criteria for membership in the young stellar association. One of them, UScoJ155150.2–213457, is a new discovery. We obtained low resolution, near-infrared spectroscopy ($R \sim 450$, 0.85–2.35 $\mu$m) of this new finding using the FIRE instrument. We confirmed its low-gravity atmosphere expected for an Upper Scorpius member (weak alkaline lines, strong VO absorption, peaked $H$-band pseudocontinuum). By comparison with spectroscopic standards, we derive a spectral type of L6±1, and estimate a mass of 0.008–0.010 $M_\odot$ for UScoJ155150.2–213457. The colors and spectral slope of this object resemble those of other young, cool members of Upper Scorpius and $\sigma$ Orionis (∼3 Myr) and field, high gravity dwarfs of related classification in contrast with the very red indices of field, low gravity, L-type dwarfs of intermediate age. UScoJ155150.2–213457, which does not show infrared flux excesses up to 4.5 $\mu$m, becomes one of the least massive and latest type objects known in the entire Upper Scorpius stellar association.

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Observational constraints on star cluster formation theory - I. The mass-radius relation

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Stars form predominantly in groups usually denoted as clusters or associations. The observed stellar groups display a broad spectrum of masses, sizes and other properties, so it is often assumed that there is no underlying structure in this diversity. Here we show that the assumption of an unstructured multitude of cluster or association types might be misleading. Current data compilations of clusters in the solar neighbourhood show correlations between cluster mass, size, age, maximum stellar mass etc. In this first paper we take a closer look at the correlation of cluster mass and radius. We use literature data to explore relations in cluster and molecular core properties in the solar neighbourhood. We show that for embedded clusters in the solar neighbourhood there exists a clear correlation between cluster mass and half-mass radius of the form $M_c = C R_c^\gamma$ with $\gamma = 1.7 \pm 0.2$. This correlation holds for infrared $K$ band data as well as X-ray sources and for clusters containing a hundred stars up to those consisting of a few tens of thousands of stars. The correlation is difficult to verify for clusters containing <30 stars due to low-number statistics. Dense clumps of gas are the progenitors of the embedded clusters. We find a similar slope for the mass–size relation of dense, massive clumps as for the embedded star clusters. This might point at a direct translation from gas to stellar mass: however, it is difficult to relate size measurements for clusters (stars) to those for gas profiles. Taking into account multiple paths for clump mass into cluster mass, we obtain an average star-formation efficiency of $18\%^{+5.7}_{-3.9}$ for the embedded clusters in the solar neighborhood. The derived mass–radius relation gives constraints for the theory of clustered star formation. Analytical models and simulations of clustered star formation have to reproduce this relation in order to be realistic.

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A tunnel and a traffic jam: How transition disks maintain a detectable warm dust component despite the presence of a large planet-carved gap

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Context. Transition disks are circumstellar disks that show evidence of a dust cavity, which may be related to dynamical clearing by embedded planet(s). Most of these objects show signs of significant accretion, indicating that the inner disks are not truly empty, but that gas is still streaming through to the star. A subset of transition disks, sometimes called pre-transition disks, also shows a strong near-infrared excess, interpreted as an optically thick dusty belt located close to the dust sublimation radius within the first astronomical unit.

Aims. We study the conditions for the survival and maintenance of such an inner disk in the case where a massive planet opens a gap in the disk. In this scenario, the planet filters out large dust grains that are trapped at the outer edge of the gap, while the inner regions of the disk may or may not be replenished with small grains.

Methods. We combined hydrodynamical simulations of planet-disk interactions with dust evolution models that include coagulation and fragmentation of dust grains over a large range of radii and derived observational properties using radiative transfer calculations. We studied the role of the snow line in the survival of the inner disk of transition disks.

Results. Inside the snow line, the lack of ice mantles in dust particles decreases the sticking efficiency between grains. As a consequence, particles fragment at lower collision velocities than in regions beyond the snow line. This effect allows small particles to be maintained for up to a few Myrs within the first astronomical unit. These particles are closely coupled to the gas and do not drift significantly with respect to the gas. For lower mass planets ($1 \ M_{\text{Jup}}$), the pre-transition appearance can be maintained even longer because dust still trickles through the gap created by the planet, moves invisibly and quickly in the form of relatively large grains through the gap, and becomes visible again as it fragments and gets slowed down inside of the snow line.

Conclusions. The global study of dust evolution of a disk with an embedded planet, including the changes of the dust aerodynamics near the snow line, can explain the concentration of millimetre-sized particles in the outer disk and the survival of the dust in the inner disk if a large dust trap is present in the outer disk. This behaviour solves the conundrum of the combination of both near-infrared excess and ring-like millimetre emission observed in several transition disks.

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C/O and Snowline Locations in Protoplanetary Disks: The Effect of Radial Drift and Viscous Gas Accretion

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The C/O ratio is a defining feature of both gas giant atmospheric and protoplanetary disk chemistry. In disks, the C/O ratio is regulated by the presence of snowlines of major volatiles at different distances from the central star. We explore the effect of radial drift of solids and viscous gas accretion onto the central star on the snowline locations of the main C and O carriers in a protoplanetary disk, $\text{H}_2\text{O}$, CO$_2$ and CO, and their consequences for the C/O ratio in gas and dust throughout the disk. We determine the snowline locations for a range of fixed initial particle sizes and disk types. For our fiducial disk model, we find that grains with sizes $\sim0.5$ cm $< s < 7$ m for an irradiated disk, and $\sim0.001$ cm $< s < 7$ m for an evolving and viscous disk, desorb at a size-dependent location in the disk, which is independent of the particle’s initial position. The snowline radius decreases for larger particles, up to sizes of $\sim7$ m. Compared to a static disk, we find that radial drift and gas accretion in a viscous disk move the $\text{H}_2\text{O}$ snowline inwards by up to 40%, the CO$_2$ snowline by up to 60%, and the CO snowline by up to 50%. We thus determine an
inner limit on the snowline locations when radial drift and gas accretion are accounted for.

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Results from DROXO IV. EXTraS discovery of an X-ray flare from the Class I protostar candidate ISO-Oph 85

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X-ray emission from Young Stellar Objects (YSOs) is a key ingredient in understanding star formation. For the early, protostellar (Class I) phase, a very limited (and controversial) quantity of X-ray results is available to date. Within the EXTraS (Exploring the X-ray Transient and variable Sky) project, we have discovered transient X-ray emission from a source whose counterpart is ISO-Oph 85, a strongly embedded YSO in the \( \rho \) Ophiuchi star-forming region.

We extract an X-ray light curve for the flaring state, and determine the spectral parameters for the flare from XMM-Newton/EPIC data with a method based upon quantile analysis. We combine photometry from infrared to millimeter wavelengths from the literature with mid-IR Spitzer and unpublished submm Herschel photometry that we analysed for this work, and we describe the resulting SED with a set of precomputed models.

The X-ray flare of ISO-Oph 85 lasted \( \sim 2500 \) s and is consistent with a highly-absorbed one-component thermal model (\( N_H = 1.0^{+1.2}_{-0.5} \cdot 10^{23} \text{ cm}^{-2} \) and \( kT = 1.15^{+2.35}_{-0.65} \text{ keV} \)). The X-ray luminosity during the flare is log \( L_X \ [\text{erg/s}] = 31.1^{+2.10}_{-1.2} \). During quiescence we set an upper limit of log \( L_X \ [\text{erg/s}] < 29.5 \). We do not detect other flares from this source. The submillimeter fluxes suggest that the object is a Class I protostar. We caution, however, that the offset between the Herschel and optical/infrared position is larger than that for other YSOs in the region, leaving some doubt on this association.

To the best of our knowledge, this is the first X-ray flare from a YSO that has been recognised as a candidate Class I protostar via the analysis of its complete SED, including the submm bands that are crucial for detecting the protostellar envelope. This work shows how the analysis of the whole SED is fundamental to the classification of YSOs, and how the X-ray source detection techniques we have developed can open a new era in time-resolved analysis of the X-ray emission from stars.

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SMA observations of the W3(OH) complex: Dynamical differentiation between W3(H$_2$O) and W3(OH)

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We present Submillimeter Array (SMA) observations of the HCN (3–2) and HCO$^+$ (3–2) molecular lines toward the W3(H$_2$O) and W3(OH) star-forming complexes. Infall and outflow motions in the W3(H$_2$O) have been characterized by observing HCN and HCO$^+$ transitions. High-velocity blue/red-shifted emission, tracing the outflow, show multiple knots, which might originate in episodic and precessing outflows. ‘Blue-peaked’ line profiles indicate that gas is infalling onto the W3(H$_2$O) dust core. The measured large mass accretion rate, $2.3 \times 10^{-3}$ M$_\odot$ yr$^{-1}$, together with the small free-fall time scale, $5 \times 10^3$ yr, suggest W3(H$_2$O) is in an early evolutionary stage of the process of formation of high-mass stars. For the W3(OH), a two-layer model fit to the HCN and HCO$^+$ spectral lines and Spitzer/IRAC images support that the W3(OH) H$\alpha$ region is expanding and interacting with the ambient gas, with the shocked neutral gas being expanding with an expansion timescale of $6.4 \times 10^3$ yr. The observations suggest different kinematical timescales and dynamical states for the W3(H$_2$O) and W3(OH).

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Detectability of deuterated water in prestellar cores

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Water is an important molecule in the chemical and thermal balance of dense molecular gas, but knowing its history throughout the various stages of the star formation is a fundamental problem. Its molecular deuteration provides us with a crucial clue to its formation history. H$_2$O has recently been detected for the first time towards the prestellar core L1544 with the Herschel Space Observatory with a high spectral resolution (HIFI instrument). Prestellar cores provide the original reservoir of material from which future planetary systems are built, but few observational constraints exist on the formation of water and none on its deuteration before the collapse starts and a protostar forms at the centre. We report on new APEX observations of the ground state $^1$0$_{0,1}$-0$_{0,0}$ HDO transition at 464 GHz towards the prestellar core L1544. The line is undetected, and we present an extensive study of the conditions for its detectability in cold and dense cloud cores. The water and deuterated water abundances have been estimated using an advanced chemical model simplified for the limited number of reactions or processes that are active in cold regions ($\leq 15$ K). We use the LIME radiative transfer code to compute the expected intensity and profile of both H$_2$O and HDO lines and compare them with the observations. We present several ad hoc profiles that best-fit the observations and compare the profiles with results from an astrochemical modelling, coupling gas phase and grain surface chemistry. Our comparison between observations, radiative transfer, and chemical modelling shows the limits of detectability for singly deuterated water, through the ground-state transitions $^1$0$_{0,1}$-0$_{0,0}$ and $^1$1$_{1,1}$-0$_{0,0}$ at 464.9 and 893.6 GHz, respectively, with both single-dish...
telescope and interferometric observations.

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Accreting Protoplanets in the LkCa 15 Transition Disk

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Exoplanet detections have revolutionized astronomy, offering new insights into solar system architecture and planet demographics. While nearly 1900 exoplanets have now been discovered and confirmed, none are still in the process of formation. Transition discs, protoplanetary disks with inner clearings best explained by the influence of accreting planets, are natural laboratories for the study of planet formation. Some transition discs show evidence for the presence of young planets in the form of disc asymmetries or infrared sources detected within their clearings, as in the case of LkCa 15. Attempts to observe directly signatures of accretion onto protoplanets have hitherto proven unsuccessful. Here we report adaptive optics observations of LkCa 15 that probe within the disc clearing. With accurate source positions over multiple epochs spanning 2009–2015, we infer the presence of multiple companions on Keplerian orbits. We directly detect Hα emission from the innermost companion, LkCa 15 b, evincing hot (∼10,000 K) gas falling deep into the potential well of an accreting protoplanet.

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Linking low- to high-mass YSOs with Herschel-HIFI observations of water

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Water probes the dynamics in young stellar objects (YSOs) effectively, especially shocks in molecular outflows. It is a key molecule for exploring whether the physical properties of low-mass protostars can be extrapolated to massive YSOs. As part of the WISH key programme, we investigate the dynamics and the excitation conditions of shocks along the outflow cavity wall as function of source luminosity. Velocity-resolved Herschel-HIFI spectra of the H2O 988, 752, 1097 GHz and 12CO J=10–9, 16–15 lines were analysed for 52 YSOs with bolometric luminosities (Lbol)
Jet multiplicity in the proto-binary system NGC1333-IRAS4A. The detailed CALYPSO IRAM-PdBI view

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Owing to the paucity of sub-arcsecond (sub)mm observations required to probe the innermost regions of newly forming protostars, several fundamental questions are still being debated, such as the existence and coevality of close multiple systems. We study the physical and chemical properties of the jets and protostellar sources in the NGC1333-IRAS4A proto-binary system using continuum emission and molecular tracers of shocked gas. We observed NGC1333-IRAS4A in the SiO(6−5), SO(65−54), and CO(2−1) lines and the continuum emission at 1.3, 1.4, and 3 mm using the IRAM Plateau de Bure Interferometer in the framework of the CALYPSO large program. We clearly disentangle for the first time the outflow emission from the two sources A1 and A2. The two protostellar jets have very different properties: the A1 jet is faster, has a short dynamical timescale (<103 yr), and is associated with H2 shocked emission, whereas the A2 jet, which dominates the large-scale emission, is associated with diffuse emission, bends, and emits at slower velocities. The observed bending of the A2 jet is consistent with the change of propagation direction observed at large scale and suggests jet precession on very short timescales (~200–600 yr). In addition, a chemically rich spectrum with emission from several COMs (e.g. HCOOH, CH3OCHO, CH3OCH3) is only detected towards A2. Finally, very high-velocity shocked emission (~50 km s−1) is observed along the A1 jet. An LTE analysis shows that SiO, SO, and H2CO abundances in the gas phase are enhanced up to (3−4) × 10−7, (1.4–1.7) × 10−6, and (3−7.9) × 10−7, respectively. The intrinsic different properties of the jets and driving sources in NGC1333-IRAS4A suggest different evolutionary stages for the two protostars, with A1 being younger than A2, in a very early stage of star formation previous to the hot-corino phase.

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The nature of the 2014–2015 dim state of RW Aur revealed by X-ray, optical, and NIR observations

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The binary system RW Aur consists of two classical T Tauri stars (CTTSs). The primary recently underwent its second observed major dimming event ($\Delta V \sim 2$mag). We present new, resolved Chandra X-ray and UKIRT near-IR (NIR) data as well as unresolved optical photometry obtained in the dim state to study the gas and dust content of the absorber causing the dimming. The X-ray data show that the absorbing column density increased from $N_{\text{H}} < 0.1 \times 10^{22}$ cm$^{-2}$ during the bright state to $\approx 2 \times 10^{22}$ cm$^{-2}$ in the dim state. The brightness ratio between dim and bright state at optical to NIR wavelengths shows only a moderate wavelength dependence and the NIR color-color diagram suggests no substantial reddening. Taken together, this indicates gray absorption by large grains ($\gtrsim 1$?m) with a dust mass column density of $\gtrsim 2 \times 10^{-4}$ g cm$^{-2}$. Comparison with $N_{\text{H}}$ shows that an absorber responsible for the optical/NIR dimming and the X-ray absorption is compatible with the ISM’s gas-to-dust ratio, i.e., that grains grow in the disk surface layers without largely altering the gas-to-dust ratio. Lastly, we discuss a scenario in which a common mechanism can explain the long-lasting dimming in RW Aur and recently in AA Tau.

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Resonant Removal of Exomoons During Planetary Migration

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Jupiter and Saturn play host to an impressive array of satellites, making it reasonable to suspect that similar systems of moons might exist around giant extrasolar planets. Furthermore, a significant population of such planets is known to reside at distances of several Astronomical Units (AU), leading to speculation that some moons thereof might support liquid water on their surfaces. However, giant planets are thought to undergo inward migration within their natal protoplanetary disks, suggesting that gas giants currently occupying their host star’s habitable zone formed further out. Here we show that when a moon-hosting planet undergoes inward migration, dynamical interactions may naturally destroy the moon through capture into a so-called “ejection resonance.” Within this resonance, the lunar orbit’s eccentricity grows until the moon eventually collides with the planet. Our work suggests that moons orbiting within about 10 planetary radii are susceptible to this mechanism, with the exact number dependent upon the planetary mass, oblateness and physical size. Whether moons survive or not is critically related to where the planet began its inward migration as well as the character of inter-lunar perturbations. For example, a Jupiter-like planet currently residing at 1 AU could lose moons if it formed beyond 5 AU. Cumulatively, we suggest that an observational census of exomoons could potentially inform us on the extent of inward planetary migration, for which no reliable observational proxy currently exists.

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A study of the C$_3$H$_2$ isomers and isotopologues: first interstellar detection of HDCCC

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The partially deuterated linear isomer HDCCC of the ubiquitous cyclic carbene ($c$-C$_3$H$_2$) was observed in the starless cores TMC-1C and L1544 at 96.9 GHz, and a confirming line was observed in TMC-1 at 19.38 GHz. To aid the identification in these narrow line sources, four centimetre-wave rotational transitions (two in the previously reported $K_a = 0$ ladder, and two new ones in the $K_a = 1$ ladder), and 23 transitions in the millimetre band between 96 and 272 GHz were measured in high-resolution laboratory spectra. Nine spectroscopic constants in a standard asymmetric top Hamiltonian allow the principal transitions of astronomical interest in the $K_a \leq 3$ rotational ladders to be calculated to within 0.1 km s$^{-1}$ in radial velocity up to 400 GHz. Conclusive evidence for the identification of the two astronomical lines of HDCCC was provided by the $V_{LSR}$ which is the same as that of the normal isotopic species (H$_2$CCC) in the three narrow line sources. In these sources, deuterium fractionation in singly substituted H$_2$CCC (HDCCC/H$_2$CCC $\sim 4\%–19\%$) is comparable to that in c-C$_3$H$_2$ (c-C$_3$H$_2$/c-C$_3$HD $\sim 5\%–17\%$), and similarly in doubly deuterated c-C$_3$H$_2$ (c-C$_3$D$_2$/c-C$_3$HD $\sim 3\%–17\%$), implying that the efficiency of the deuteration processes in the H$_2$CCC and c-C$_3$H$_2$ isomers are comparable in dark clouds.

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A search for High Mass Stars Forming in Isolation using CORNISH & ATLASGAL

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Theoretical models of high mass star formation lie between two extreme scenarios. At one extreme, all the mass comes from an initially gravitationally-bound core. At the other extreme, the majority of the mass comes from cluster scale gas, which lies far outside the initial core boundary. One way to unambiguously show high mass stars can assemble their gas through the former route would be to find a high mass star forming in isolation. Making use of recently available CORNISH and ATLASGAL Galactic plane survey data, we develop sample selection criteria to try and find such an object. From an initial list of approximately 200 sources, we identify the high mass star forming region G13.384+0.064 as the most promising candidate. The region contains a strong radio continuum source, that is powered by an early B-type star. The bolometric luminosity, derived from infrared measurements, is consistent with this. However, sub-millimetre continuum emission, measured in ATLASGAL, as well as dense gas tracers, such as HCO$^+$(3–2) and N$_2$H$^+$(3–2) indicate that there is less than 100 $M_\odot$ of material surrounding this star. We conclude that this region is indeed a promising candidate for a high mass star forming in isolation, but that deeper near-IR observations are required to put a stronger constraint on the upper mass limit of young, lower mass stars in the region. Finally, we discuss the challenges facing future studies in proving a given high mass star is forming in isolation.

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Resolved gas cavities in transitional disks inferred from CO isotopologues with ALMA

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Transitional disks around young stars with large dust cavities are promising candidates to look for recently formed, embedded planets. Planet-disk interaction models predict that young planets clear a gap in the gas while trapping dust at larger radii. Other physical mechanisms could be responsible for cavities as well. Previous observations have revealed that gas is still present inside these cavities, but the spatial distribution of this gas remains uncertain. We present high spatial resolution observations with the Atacama Large Millimeter/submillimeter Array (ALMA) of ¹³CO and C¹⁸O 3–2 or 6–5 lines of four well-studied transitional disks around pre-main sequence stars with large dust cavities. The line and continuum observations are used to set constraints on the gas surface density, specifically cavity size and density drop inside the cavity. The physical-chemical model DALI is used to analyze the gas images of SR21, HD135344B (also known as SAO 206462), DoAr44 and IRS 48. The main parameters of interest are the size, depth and shape of the gas cavity in each of the disks. CO isotope-selective photodissociation is included to properly constrain the surface density in the outer disk from C¹⁸O emission. The gas cavities are up to 3 times smaller than those of the dust in all four disks. Model fits indicate that the surface density inside the gas cavities decreases by a factor of 100 to 1000 compared with the surface density profile derived from the outer disk. The data can be fit by either introducing one or two drops in the gas surface density or a surface density profile increasing with radius inside the cavity. A comparison with an analytical model of gap depths by planet-disk interaction shows that the disk viscosities are likely low, between between 10⁻³ and 10⁻⁴ for reasonable estimates of planet masses up to 10 Jupiter masses. The resolved measurements of the gas and dust in transition disk cavities support the predictions of models that describe how planet-disk interactions sculpt gas disk structures and influence the evolution of dust grains. These observed structures strongly suggest the presence of giant planetary companions in transition disk cavities, although at smaller orbital radii than is typically indicated from the dust cavity radii alone.

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Star formation towards the southern Cometary H II region IRAS 17256–3631

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IRAS 17256–3631 is a southern Galactic massive star forming region located at a distance of 2 kpc. In this paper, we present a multiwavelength investigation of the embedded cluster, the H II region, as well as the parent cloud. Radio images at 325, 610 and 1372 MHz were obtained using GMRT, India while the near-infrared imaging and spectroscopy were carried out using UKIRT and Mt. Abu Infrared Telescope, India. The near-infrared K-band image reveals the presence of a partially embedded infrared cluster. The spectral features of the brightest star in the cluster, IRS-1, spectroscopically agrees with a late O or early B star and could be the driving source of this region. Filamentary H₂ emission detected towards the outer envelope indicates presence of highly excited gas. The parent cloud is investigated at far-infrared to millimeter wavelengths and eighteen dust clumps have been identified. The spectral energy distributions (SEDs) of these clumps have been fitted as modified blackbodies and the best-fit peak temperatures are found to range from 14 – 33 K, while the column densities vary from 0.7 – 8.5 x 10²² cm⁻². The radio
maps show a cometary morphology for the distribution of ionised gas that is density bounded towards the north-west and ionization bounded towards the south-east. This morphology is better explained with the champagne flow model as compared to the bow shock model. Using observations at near, mid and far-infrared, submillimeter and radio wavelengths, we examine the evolutionary stages of various clumps.

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Consistent dust and gas models for protoplanetary disks. I. Disk shape, dust settling, opacities, and PAHs

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We propose a set of standard assumptions for the modelling of Class II and III protoplanetary disks, which includes detailed continuum radiative transfer, thermo-chemical modelling of gas and ice, and line radiative transfer from optical to cm wavelengths. We propose new standard dust opacities for disk models, we present a simplified treatment of PAHs sufficient to reproduce the PAH emission features, and we suggest using a simple treatment of dust settling. We roughly adjust parameters to obtain a model that predicts typical Class II T Tauri star continuum and line observations. We systematically study the impact of each model parameter (disk mass, disk extension and shape, dust settling, dust size and opacity, gas/dust ratio, etc.) on all continuum and line observables, in particular on the SED, mm-slope, continuum visibilities, and emission lines including [OI] 63\,\mu m, high-J CO lines, (sub-)mm CO isotopologue lines, and CO fundamental ro-vibrational lines. We find that evolved dust properties (large grains) often needed to fit the SED, have important consequences for disk chemistry and heating/cooling balance, leading to stronger emission lines in general. Strong dust settling and missing disk flaring have similar effects on continuum observations, but opposite effects on far-IR gas emission lines. PAH molecules can shield the gas from stellar UV radiation because of their strong absorption and negligible scattering opacities. The observable millimetre-slope of the SED can become significantly more gentle in the case of cold disk midplanes, which we find regularly in our T Tauri models. We propose to use line observations of robust chemical tracers of the gas, such as O, CO, and H\textsubscript{2}, as additional constraints to determine some key properties of the disks, such as disk shape and mass, opacities, and the dust/gas ratio, by simultaneously fitting continuum and line observations.

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Inclination-Induced Polarization of Scattered Millimeter Radiation from Protoplanetary Disks: The Case of HL Tau

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Spatially resolved polarized millimeter/submillimeter emission has been observed in the disk of HL Tau and two other young stellar objects. It is usually interpreted as coming from magnetically aligned grains, but can also be produced by dust scattering, as demonstrated explicitly by Kataoka et al. for face-on disks. We extend their work by including the polarization induced by disk inclination with respect to the line of sight. Using a physically motivated, semi-analytic model, we show that the polarization fraction of the scattered light increases with the inclination angle, reaching 1/3 for edge-on disks. The inclination-induced polarization can easily dominate that intrinsic to the disk in the face-on view. It provides a natural explanation for the two main features of the polarization pattern observed in the tilted disk of HL Tau ($i \sim 45^\circ$): the polarized intensity concentrating in a region elongated more or less along the major axis, and polarization in this region roughly parallel to the minor axis. This broad agreement provides support to dust scattering as a viable mechanism for producing, at least in part, polarized millimeter radiation. In order to produce polarization at the observed level ($\sim 1\%$), the scattering grains must have grown to a maximum size of tens of microns. However, such grains may be too small to produce the opacity spectral index of $\beta \lesssim 1$ observed in HL Tau and other sources; another population of larger, millimeter/centimeter-sized, grains may be needed to explain the bulk of the unpolarized continuum emission.

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First light of the VLT planet finder SPHERE. III. New spectrophotometry and astrometry of the HR8799 exoplanetary system


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The planetary system discovered around the young A-type HR8799 provides a unique laboratory to: a) test planet formation theories, b) probe the diversity of system architectures at these separations, and c) perform comparative (exo)planetology. We present and exploit new near-infrared images and integral-field spectra of the four gas giants surrounding HR8799 obtained with SPHERE, the new planet finder instrument at the Very Large Telescope, during the commissioning and science verification phase of the instrument (July-December 2014). With these new data, we contribute to completing the spectral energy distribution of these bodies in the 1.0–2.5 μm range. We also provide new astrometric data, in particular for planet e, to further constrain the orbits. We used the infrared dual-band imager and spectrograph (IRDIS) subsystem to obtain pupil-stabilized, dual-band $H_2H_3$ (1.593 μm, 1.667 μm), $K1K2$ (2.110 μm, 2.251 μm), and broadband $J$ (1.245 μm) images of the four planets. IRDIS was operated in parallel with the integral field spectrograph (IFS) of SPHERE to collect low-resolution ($R \sim 30$), near-infrared (0.94–1.64 μm) spectra of the two innermost planets HR8799d and e. The data were reduced with dedicated algorithms, such as the Karhunen-Loève image projection (KLIP), to reveal the planets. We used the so-called negative planets injection technique to extract their photometry, spectra, and measure their positions. We illustrate the astrometric performance of SPHERE through sample orbital fits compatible with SPHERE and literature data.

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http://arxiv.org/pdf/1511.04083
Multi-wavelength, Multi-scale Observations of Outflows in Star-Forming Regions

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During the early stages of star formation, an embedded protostar accretes mass and simultaneously expels mass and angular momentum in the form of a bipolar outflow. In the common case of clustered star formation, outflows likely impact their surrounding environment and influence subsequent star formation. Numerical simulations have shown that outflows can sustain turbulence and maintain a cluster in quasi-equilibrium; alternatively, it was proposed that outflows may trigger rather than regulate or inhibit star formation. Observations of outflows and their impact on clusters are challenging because they must probe spatial scales over several orders of magnitude — from the size of a core (a few hundred AU, or \( \sim 10^{-3} \) pc) to a cluster (a few pc) — and previous works generally focused on one scale or the other. This thesis incorporates high-resolution, high-sensitivity interferometry observations (with millimeter/sub-millimeter wavelengths) complemented by observations obtained using single dish telescopes in order to assess molecular outflow properties and their cumulative impact in two young protostellar clusters: Serpens South and NGC 1333. Based on these case studies, I develop an evolutionary scenario for clustered star formation spanning the ages of the two clusters, about 0.1 - 1 Myr. Within this scenario, outflows in both Serpens South and NGC 1333 provide sufficient energy to sustain turbulence early in the protocluster formation process. In neither cluster do outflows provide enough energy to counter the gravitational potential energy and disrupt the entire cluster. However, most of the mass in outflows in both clusters have velocities greater than the escape velocity, and therefore the relative importance of outflow-driven turbulence compared with gravitational potential likely changes with time as ambient gas escapes. We estimate that enough gas mass will escape via outflows in Serpens South so that it will come to resemble NGC 1333 in terms of its ratio of outflow energy to gravitational binding energy; further, if gas escapes from NGC 1333, then outflow energy and gravitational energy may become comparable within the next \( \sim 0.5 \) Myr, possibly disrupting the cluster. Finally, we investigate the properties of a particular Class 0 molecular outflow in Serpens South, providing evidence for episodic outflow events and corresponding accretion at a very early stage. This remarkable outflow remains intact even within the active, central hub region of Serpens South.
Postdoc position in Young Stellar Objects research at the Institute for Astronomy and Astrophysics in Tübingen

The Institute for Astronomy and Astrophysics of University Tübingen (IAAT) invites applications for a postdoc position in the research group led by Dr Manami Sasaki on the project: "Supernova remnant shock impact on star formation" within the framework of the Heisenberg programme of the German Research Foundation. The research group is affiliated to the High-Energy Astrophysics group of IAAT and the Kepler Center for Astro and Particle Physics. The activities of the High-Energy Astrophysics group of IAAT include data analysis and modeling in X-ray and Gamma-ray Astronomy as well as hardware development.

The successful candidate will be involved in the study of young stellar objects (YSOs) found in the close vicinity of supernova remnants (SNRs) that are known to show interaction with molecular clouds. The aim of the project is to study the following science questions:

- How do shock waves affect the evolution of pre-existing YSOs and in particular their discs?
- Can SNR shocks benefit planet formation in the discs? Are they responsible for the metal enrichment as observed in the Solar system?

The postdoc will also have the opportunity to participate in the research in High-Energy Astrophysics and in particular in the eROSITA activities of the group.

Applicants should hold a Ph.D. in Physics or Astrophysics and have expertise in YSO studies, in particular in the Physics of accretion disks and outflows. In addition, experience in studies of molecular clouds would be advantageous.

The appointment can start as soon as possible. The position is initially limited to 2 years. The salary is based on the German salary scale TVL E13.

Tübingen University aims to increase the number of women in research and education, thus women are strongly encouraged to apply.

Please send your application including a cover letter (indicating preferred starting date), together with a CV, list of publications, short statement of research interests, and two letters of reference electronically to: sasaki@astro.uni-tuebingen.de. The deadline is December 31, 2015, but applications will be accepted until the position is filled.

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### Resolving Planet Formation in the Era of Alma and Extreme AO

**May 16-20, 2016 Santiago, Chile**

[http://www.eso.org/sci/meetings/2016/Planet-Formation2016.html](http://www.eso.org/sci/meetings/2016/Planet-Formation2016.html)

Results from ALMA Long Baseline observations and from SPHERE, GPI and other high-contrast AO instruments have given a taste of what to expect over the next few years in the fields of protoplanetary and debris disks, and planet formation. For the first time, these instruments are enabling us to observe the regions where planets form. Already we are finding gaps, holes, spiral wave patterns, and extreme asymmetries in the disks.

Substantially different structures are seen in various molecules and in different dust grains, and the first evidence for the detection of young planets is starting to emerge.

With the few-AU scales now resolvable, we can also start to unravel the complex dynamical interaction between the disks, accretion, jets and winds, and how these affect the growing planets.

Some of these spectacular features had been predicted by theory but confrontation with current models indicates clearly that we still have much to learn about what happens within 100AU of young stars.

We will host an ESO planet formation workshop in 2016 to discuss the state of the art results in this field. The program will offer a panchromatic view of the latest results, with an adequate balance between observations and theory. The timescale for this international conference is propitious, fostering discussions on how upcoming facilities (such as JWST, TMT and eELT) and advances in modeling will tackle planetary formation in the next few years.

*Conference email:* planet-formation2016@eso.org

*Organizers:* ESO, ALMA, NAOJ, NRAO

### VIALACTEA 2016: the Milky Way as a Star Formation Engine

**Rome, September 26-30, 2016**

[http://vialactea2016.iaps.inaf.it](http://vialactea2016.iaps.inaf.it)

The Milky Way Galaxy is a complex ecosystem where a cyclical transformation process brings diffuse baryonic matter into dense unstable condensations to form stars. They produce radiant energy for billions of years before releasing chemically enriched material back into the Inter Stellar Medium in their final stages of evolution. Star formation is the trigger of this process, eventually driving the evolution of ordinary matter in the Universe, from its primordial composition to the present-day chemical diversity necessary for the birth of life.

Although considerable progress has been made in the last two decades in the understanding of the evolution of isolated dense molecular clumps toward the onset of gravitational collapse and the formation of stars and planetary systems, several key-questions remain elusive.

- What is the relative importance of gravity, turbulence or the perturbation from spiral arms in assembling the diffuse and mostly atomic Galactic ISM into molecular dense filamentary structures and compact clumps ?
- How do turbulence, gravity, external triggers, chemistry and magnetic fields interact on different spatial scales to bring a diffuse cloud on the verge of star formation ?
- How do the relative weights of these different agents change from extreme environments like the Galactic Center to the quiet neighborhoods of the Galaxy beyond the solar circle ?
- How can we quantitatively relate the different physical agents at work, to the rate and the efficiency with which they are able to turn gas and dust into stars ?
How these results fit in / complement the current high resolution view of star formation?

The creation of a fundamental theory or, rather, of a galaxy-scale predictive model for star formation, is a key challenge. We enter a new era where a new suite of cutting-edge Milky Way surveys of the entire Galactic Plane have already started to transform the view of our Galaxy as a global star formation engine. The combination of near-IR ground surveys data, mid-IR and far-IR dust continuum obtained by ESA’s HERSCHEL and NASA’s SPITZER and WISE satellites, with submillimeter and radio continuum and gas-tracing atomic and molecular spectroscopy from ground-based antennas, is for the first time unlocking access to angular scales below 30” across 4 decades in wavelength for both the dust and the three gas components of the ISM (molecular, atomic and ionised).

The integrated science analysis of these massive and diverse datasets requires new concepts of 3D-based visual analytics tools that integrate data access, sources and features extraction, model fitting and source classifications.

Five years after the successful MW2011 Congress in Rome, this conference marks the conclusion of the EU-funded FP7 Collaborative Project "VIALACTEA", whose objectives and aims inspire the main topics of the conference.

VIALACTEA 2016 aims at promoting advances in a number of fields:

- Inter Stellar Medium, Molecular clouds and Filaments: from the diffuse texture of the ISM to the backbone skeleton of the Milky Way
- Demographics of Galactic Clumps and Cluster Progenitors: conditions, timelines, rates and efficiencies of cluster and massive star formation as a function of mass and environment
- Triggering, Spiral Arms, Turbulence and Gravitation: sifting the ingredients of a Galactic Star Formation Recipe.
- The 3-D Galaxy from the near-infrared to the radio
- The Milky Way in the context of its surrounding environment, nearby galaxies and of extra-galactic star formation recipes.
- Current high resolution view of the dynamics and chemistry of star formation from ALMA, NEOMA, etc.
- Dust and gas chemistry: the role of dust, atoms, ions and molecules in the thermodynamics of star formation, and their use as diagnostic probes and chemical clocks.
- Visual analytics, data mining and science gateways: new tools for an integrated science analysis of multi-wavelengths Galactic surveys in the Virtual Observatory framework

We foresee stimulating formats for focused discussions, where current theoretical frameworks for each of the above topics will be critically reviewed in the light of the latest observational results. Data visualization and science analysis tools will be discussed in each topics, and we foresee sessions of demos and hands-on experience.

If you want to express your interest and be sure to receive further updates about the Conference, send an e-mail with your name and Institution to vialactea2016@iaps.inaf.it or visit the website http://vialactea2016.iaps.inaf.it

More information about confirmed invited speakers, registration opening and call for contributed talks and posters, logistics and accommodation, will be available on the website and circulated later this year or early 2016.

Scientific Organising Committee:

Sergio Molinari - INAF/IAPS, Rome (Italy), Laurent Cambrésy - Observatoire de Strasbourg (France), Annie Zavagno - LAM, Marseille (France), Melvin Hoare - University of Leeds (UK), Anthony Whitworth - University of Cardiff (UK), Yasuo Fukui - Nagoya University (Japan), Chris Brunt - University of Exeter (UK), Grazia Umana - INAF/Osservatorio di Catania (Italy), Thomas Robitaille - MPIA, Heidelberg (Germany), Ugo Becciani - INAF/Osservatorio di Catania (Italy), Massimo Brescia - INAF/Osservatorio di Napoli (Italy), Toby Moore - John Moores University, Liverpool (UK), Alberto Noriega-Crespo - STScI, Baltimore (USA), Friedrich Wyrowski - MPIfR, Bonn (Germany), René Plume - University of Calgary, Calgary (Canada), André Schaaf - Observatoire de Strasbourg (France), Peter Kacsuk - SZTAKI, Budapest (Hungary), Riccardo Smareglia - INAF/Osservatorio di Trieste (Italy).
Summary of Upcoming Meetings

Protoplanetary Discussions
7 - 11 March 2016, Edinburgh, UK
http://www-star.st-and.ac.uk/ppdiscs

From Stars to Massive Stars
6 - 9 April 2016, Gainesville, Florida, USA
http://conference.astro.ufl.edu/STARSTOMASSIVE/

Water in the Universe - from Clouds to Oceans
12 - 15 April 2016, Noordwijk, The Netherlands
http://www.congrexprojects.com/2016-events/16A06/

Workshop on Young Solar Systems
18 - 22 April 2016, Barcelona, Spain

Resolving planet formation in the era of ALMA and extreme AO
16 - 20 May 2016, Santiago, Chile
http://www.eso.org/sci/meetings/2016/Planet-Formation2016.html

Diffuse Matter in the Galaxy, Magnetic Fields, and Star Formation - A Conference Honoring the Contributions of Richard Crutcher & Carl Heiles
22 - 25 May 2016, Madison, USA
http://www.astro.wisc.edu/ch16/

The 19th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun
6 - 10 June 2016 Uppsala, Sweden
http://www.coolstars19.com

Cloudy Workshop
20 - 24 June 2016 Weihai, China
http://cloudy2016.csp.escience.cn/dct/page/1

EPoS 2016 The Early Phase of Star Formation - Progress after 10 years of EPoS
26 June - 1 July 2016, Ringberg Castle, Germany

The role of feedback in the formation and evolution of star clusters
18 - 22 July 2016 Sexten, Italy

Star Formation in Different Environments
25 - 29 July 2016 Quy Nhon, Viet Nam
website to be announced

Cosmic Dust
15 - 19 August 2016, Sendai, Japan
https://www.cps-jp.org/~dust/

Star Formation 2016
21-26 August 2016 Exeter, UK
http://www.astro.ex.ac.uk/sf2016

VIALACTEA2016: The Milky Way as a Star Formation Engine
26 - 30 September 2016, Rome, Italy
http://vialactea2016.iaps.inaf.it
Notes on Star Formation

Mark R. Krumholz

This book is a series of lecture notes on star formation, based on Mark Krumholz’s course on the topic at UC Santa Cruz. It provides an introduction to the field of star formation at a level suitable for graduate students or advanced undergraduates in astronomy or physics. The structure of the book is as follows. The first two chapters begin with a discussion of observational techniques, and the basic phenomenology they reveal. The goal is to familiarize students with the basic techniques that will be used throughout, and to provide a common vocabulary for the rest of the book. The next five chapters provide a similar review of the basic physical processes that are important for star formation. Again, the goal is to provide a basis for what follows. The remaining chapters discuss star formation over a variety of scales, starting with the galactic scale and working down to the scales of individual stars and their disks. The book concludes with a brief discussion of the clearing of disks and the transition to planet formation. The book includes five problem sets, complete with solutions.

The book, of 374 pages, can be downloaded directly from arXiv at http://arxiv.org/pdf/1511.03457

It is part of The Open Astrophysics Bookshelf at http://open-astrophysics-bookshelf.github.io/

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Bibliography