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The Formation of Low-Mass Protostars and Proto-Brown Dwarfs

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Abstract. The formation of low-mass protostars and especially of brown dwarfs currently are "hot topics" in cool star research. The talks contributed to this splinter session discussed how low in mass and how low in luminosity objects might exist, if these substellar objects show evidence for circum(sub)stellar disks, and how the bottom of the mass function in young clusters after the formation process looks like. In a lively open discussion, a vast majority of the speakers and the audience expressed why, given the available data, a stellar-like formation mechanism down to the lowest masses should be preferred.

1. Introduction

Star formation is one of the great four themes of 'Origins' studied in astronomy today, and special attention is attributed to the formation of low-mass stars like our own Sun. Low-mass stars are thought to form from the collapse of a low-density interstellar molecular cloud, producing a high-density core which evolves into a flattened proto-planetary disk through which material is accreted onto the growing central object.

Large ground-based telescopes and currently active satellite observatories like *HST*, *CHANDRA*, *XMM*, and most outstandingly *SPITZER* are delivering a wealth of new details, partially forcing us to re-conceive our conceptions of star formation. At the same time, these new data are preparing the ground for *ALMA* and *Herschel*, which will come online in the near future.

The advanced numerical simulations of the complex evolution of collapsing low-mass cores are about to enter a new era with the explicit inclusion of heating and cooling by radiative transfer and with multi-wavelength modeling of high-resolution images.

However, despite all of these new high-resolution observations and simulations of low-mass star forming regions, the main controlling agents of the early phase star formation process remain highly debated. The main goal of this splinter session was to highlight ongoing progress in tackling the controlling physical processes of the formation of low-mass proto-stars and proto-brown dwarfs. All talks contributing to this splinter session came from the observational side. This bias was not intended by the conveners, but possibly may reflect the fact that most of the efforts in this field are currently done on the observational side.

2. Very low mass cores and the start of the star formation process

It became very clear again in this splinter session that in spite of the suggested scenarios that explain the formation of brown dwarfs by ejection of the least massive bodies from very young multiple systems or small-n clusters (Reipurth & Clarke 2001; Bate et al. 2003), observers in general prefer the model of star-like formation of substellar objects, i.e. via direct fragmentation of dense cores (Boss 2001; Padoan & Nordlund 2002; Whitworth et al. 2006). A large part of this session was therefore dedicated to the question of how far down in the mass spectrum low-mass cores and low-luminosity proto-substellar objects would exist, and in what numbers.

Jane Greaves reported on a new survey for low-mass cores carried out with the *SCUBA* submillimetre camera at the *JCMT*, which mapped the thermal dust emission in the Ophiucus B and D clouds. Since this emission is optically thin, core dust masses can be derived directly.

In these observations, blobs are found well into the planetary mass regime, with core masses of 10 M_{jup} and less. One 9 Jupiter-mass object even shows a bipolar outflow. The number counts of low-mass cores suggest a simple extension of the clump mass function from the stellar regime. It can be described by a simple power law of the form $dN/dlog(M) \propto M^{-0.5}$ in the range 0.003 to 10 $M_{\odot}$. Mapping deeper and deeper, new faint high density blobs appear and the bottom of the core mass function is not yet reached at 3 M_{jup}.

Neil Evans presented results from the Core-to-Disk (c2d) legacy survey with the *SPITZER* space telescope. Using *IRAC* mid-infrared data and deep optical/near-infrared images, a number of very low mass brown dwarfs with disks have been found in regions of star formation, and he addressed the question of how low in luminosity they go. The optical/near-infrared data have found the candidate young brown dwarfs, while the *SPITZER* data have identified those with disks from their infrared excess emission. Interestingly, this excess emission seems to be constant over a range of luminosities of the central object. Masses at or below 13 Jupiter masses have been inferred for the lowest-mass central objects. These are found both near cluster formation regions and far from rich clusters, indicating that ejection from clusters cannot explain the formation of all brown dwarfs.

In addition, a wide binary brown dwarf has been found in Ophiucus, which also argues against the cluster ejection scenario (Allers et al. 2005).

These results beg the question: if brown dwarfs form as stars do, where are the earlier, embedded phases. Some embedded very low luminosity objects may be the precursors of brown dwarfs with disks. A number of these have been found by the c2d project in what had been thought to be starless cores. A prominent case is the L1014 cloud, which might harbor the precursor of a young brown dwarf, although the distance to this cloud is not clear, and thus the newly detected object could be of higher mass (Young et al. 2004; Huard et al. 2006).

Jeff Linsky discussed the question of whether the EGGs in the Eagle Nebula are early stages of low-mass star or brown dwarf formation and the possible significance of the non-detection of X-rays from the EGGs. None of the EGGs are detected in X-rays with luminosity upper limits below those of pre-main sequence stars in the Orion Nebula Cluster. At the age of 2 Myrs, similar to the NGC6611 cluster whose bright stars evaporate the EGGs, young objects in the EGGs should show up in X-rays. However, the EGGs, and possible objects in them, could be much younger – their age is not really known.

3. Spectral energy distributions and evidence for disks around proto-brown dwarfs

The next two talks investigated the presence of disks around known proto-brown dwarfs, addressing the question down to which masses of the central objects disks could be detected, and if disks from very low-mass objects would show very small disk masses as well, which could be attributed to a cutoff of the disks during an ejection event.

Until recently, our detailed knowledge of substellar disks relied on a few case studies (Apai et al. 2002). Alexander Scholz reported on a program that he and his collaborators carried out to characterise disks of brown dwarfs based on large object samples using the unique capabilities of *SPITZER* combined with sensitive observations in the mm-range with the *MAMBOII* bolometer array at the IRAM 30-m antenna. The analysis of the spectral energy distributions of brown dwarfs allows them to derive the properties and evolution of these disks, and additionally to constrain the efficiency and universality of planet formation.

The study at 1.3 mm in Taurus provided mid-infrared to mm spectral energy distributions for 20 brown dwarfs, which allowed them to constrain disk masses and radii for these objects for the first time in a systematic way. Six out of the 20 brown dwarfs were actually detected at mm-wavelength, while for the others sensitive upper limits were placed. By combining these *IRAM* with *SPITZER* data, a minimum outer disc radius of 10 AU is necessary to interpret the spectral energy distributions in five cases. From these observations, there is no evidence for truncated disks due to an ejection process early in the life of brown dwarfs, which implies that most sub-stellar objects probably form in isolation.

Alexander Scholz also reported on an ongoing study of brown dwarf disks in Upper Scorpius based on *SPITZER* data. In this study, the infrared spectral energy distributions between the K-band and 24 μm of 26 brown dwarfs in Upper Scorpius, with ages of 5 Myr, are investigated. While (Carpenter et al. 2006) found no disks for solar mass stars in this region and at this age, about 37 percent of the brown dwarfs seem to have disks, although only a small fraction seems to be accreting. This would provide evidence that disks around low mass objects are longer lived than disk around solar-type stars.

José Caballero presented a correlation of objects in the region around the O9.5V-type star sigma Ori A from the *DENIS* and 2*MASS* catalogues and *IRAC* data from the *SPITZER* Space Telescope Data Archive. From the available photometry, he could produce spectral energy distributions in the IJHKs bands and at 3.6, 4.5, 5.8, and 8.0 μm for several thousand sources, and from infrared excesses infer the presence of disks surrounding a large fraction of members of the sigma Orionis cluster, from massive stars into the planetary mass regime. Especially interesting are three isolated planetary objects that show

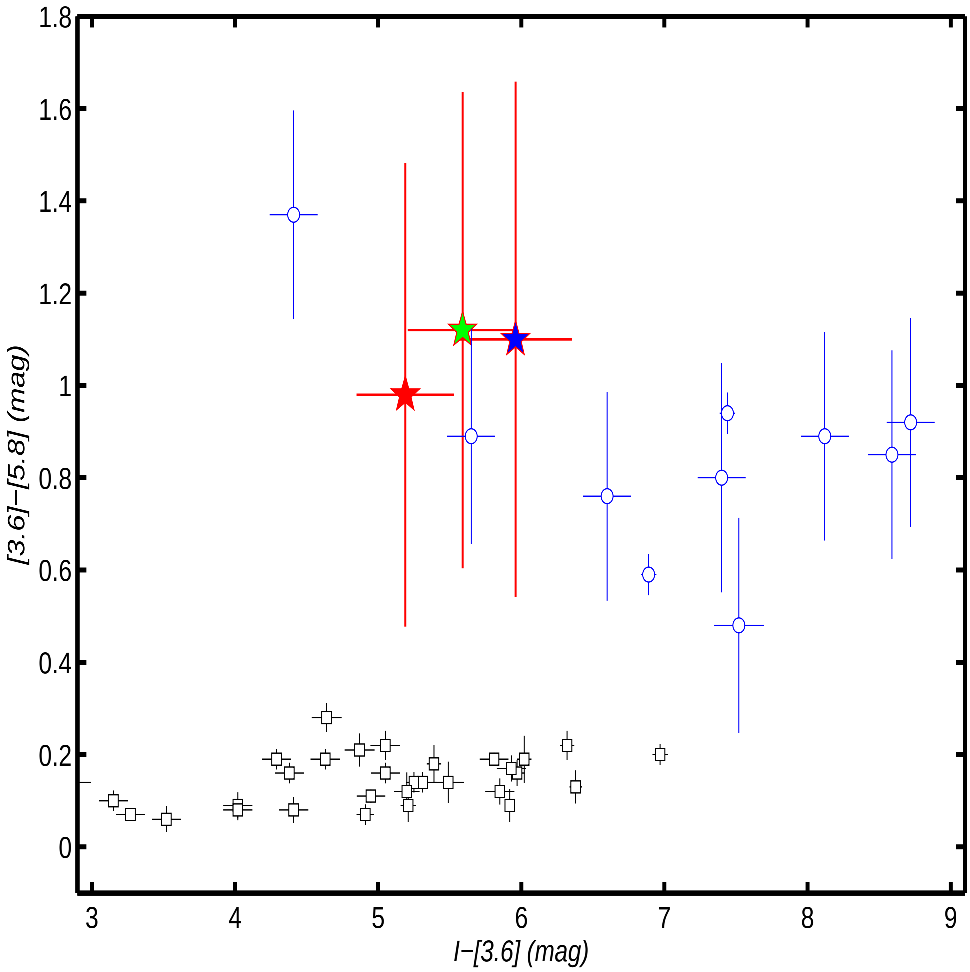

Figure 1. [3.6] − [5.8] vs. $I - [3.6]$ colour-colour diagram of three candidate isolated planetary-mass objects in σ Orionis with probable discs (big filled stars) in comparison with field ultracool dwarfs with spectral types in the range M6.5–L5.0 (open squares) and low-mass brown dwarfs and IPMOs in Chamaeleon, Ophiuchus and Lupus with discs (open circles).

infrared excess at 5.8 μm, and thus belong to the lowest mass objects with disks.

4. The mass function in the sub-stellar mass regime

Finally, Morten Anderson presented a survey in the Mon R2 cluster in JHK obtained with the *NICMOS* camera on board the *HST*. The goal of this survey was to determine if the ratio of stars to brown dwarfs is universal, and what the slope of the initial mass function (IMF) for brown dwarfs and down below the deuterium burning limit might be. This study finds a star-to-brown dwarf ratio for Mon R2 that is similar to what other studies have found for other clusters (Bejàr et al. 2001; Moraux et al. 2003), and to within 2σ is in agreement with the IMF in the solar neighborhood derived by (Chabrier 2002). Morten Anderson therefore concluded that the IMF around and below the deuterium burning limit is falling or flat, but not rising.

5. Discussion

Following these presentations, an open and lively discussion with the speakers and the audience developed about the likely formation scenario for substellar objects.

Most contributors took the view point that none of the recent observations would favor the ejection scenario. Instead everything would hint at a continuous formation process down to the lowest masses. In the absence of such evidence it would certainly seem justified to assume a common mechanism for the formation of all objects.

Very important open questions still remaining are how low in mass objects can get, and how the mass function at the very lowest masses might look like. It would also be very interesting to compare the core mass function with the mass function in young clusters. At first glance, comparing the results presented by Jane Greaves and Morten Anderson, it seems that the star formation efficiency may (strongly) drop towards lower masses. This topic certainly deserves closer investigation.

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