Probing the effects of environment on star and brown dwarf formation

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Brown dwarfs (BDs) are substellar objects not massive enough to sustain hydrogen fusion. Following this definition, we consider $75\,M_{Jup}$ ($0.072\,M_{\odot}$, the hydrogen-burning limit) as an upper mass limit for BDs. The lower mass limit is not as clear, since objects with masses below $13\,M_{Jup}$ ($0.012\,M_{\odot}$, deuterium-burning limit) not orbiting stars have been found already.

Young brown dwarfs can have effective temperatures and luminosities in the stellar range and be spectroscopically M type, then age into L dwarf regime, to end up with the temperatures of T dwarfs or massive Jovian planets [1]. BDs overlap in temperature and luminosity with both low-mass stars and planets; they also share properties with each realm. BDs not only are self-luminous, hosts to planets, discs, and outflows, but also share mass and multiplicity distributions with stars. All known BDs have similar radii (within a factor of 2) and present ultra-cool atmospheres similar to giant planet.

With such a vast combination of characteristics, BDs become one of the hot topics of modern astronomy. The question "How do such low-mass and abundant objects form?" can be naively answered in one of three possible ways: as stars, like planets or neither way. BDs can be born in the same way as very-low-mass stars through the gravitational fragmentation of infalling gas into stellar clusters [2]. Pre-stellar cores may form companion BDs in a similar way to giant planets via disk fragmentation and ejection [3]. Stellar embryos can be ejected from multiple systems during formation and thus cut-off from their accretion reservoir and evolving only into a substellar object [4]. Another viable channel for BD formation has been suggested by [5], where powerful ionisation fronts from OB stars can gradually destroy the outer layers of massive pre-stellar core, leaving a small fragment.

The current consensus is that most brown dwarfs form like stars, at least in the case of more massive BDs. Nevertheless, still, some unresolved questions in the formation of BDs need to be addressed: How far in mass does the stellar Initial Mass function (IMF) extend? Do the lowest-mass objects form "like stars" or "like planets"? Is BD formation environment dependent?

Many surveys have been dedicated to studying this problems by finding and comparing complete censuses of BDs for particular regions. Most of them, such as SONYC (Substellar Objects in Nearby Young Clusters), focuses on nearby star-forming regions (SFRs). SONYC obtained deep substellar IMF using the consistent methodology of deep optical and near-infrared photometry with spectroscopic follow-up necessary to confirm the youth and BD nature of substellar objects. The overall results from this and other surveys find the universality of low-mass end of IMF in nearby SFRs (expressed as power-law with slope $\alpha = 0.6 - 1$). They also find that for every BD formed, there are 2 to 6 stars; despite the large range, this number is consistent with a single underlying IMF. The wide range in the star-to-BD ratio is likely caused by uncertainties due to incompleteness of the spectroscopic follow-up, mass estimation, etc. and does not necessarily express the difference between regions. Strong IMF variations are excluded for most nearby SFRs. An overabundance of very low mass objects has been reported in IC 348, [6] and NGC 1333 [7], and hint that the change in environment may indeed affect the efficiency of BD formation.

The environmental difference is, in fact, theoretically expected, as most of the current BD formation theories predict an overproduction of substellar objects in dense environments or the vicinity of massive stars. To test the low mass star and brown dwarf formation across environments, we move to drastically different conditions looking for the most radical and extreme properties that can be found only in the most massive clusters. We selected three young massive clusters that encompass the wide range of initial conditions for star formation. RCW38, one of the densest and most massive young clusters; RCW36, dense, but with a few OB stars, and NGC2244, which is loose and rich in OB stars. Studying massive clusters brings many challenges for data reduction and analysis, from which the most important are: distance and high extinction due to the high column density molecular clouds with which they are associated, and in some cases crowding.

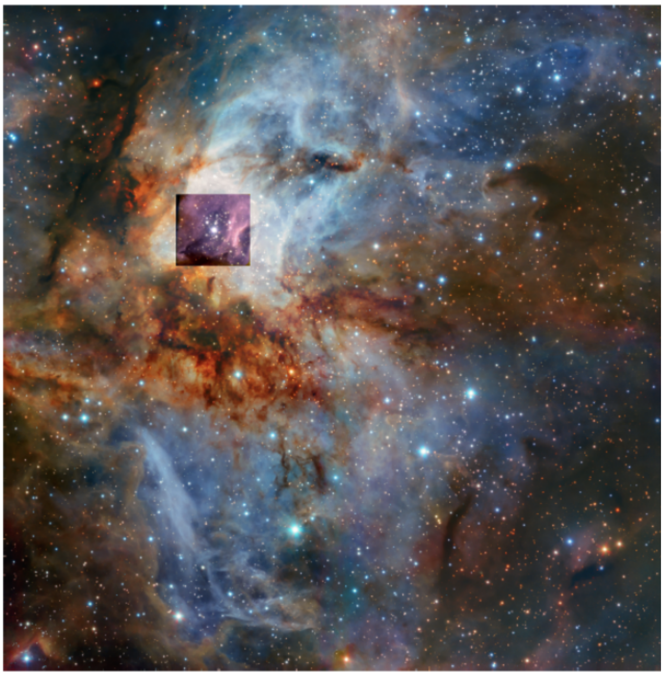

Figure 1: JHK colour-composite of RCW 38 obtained with Hawk-I/GRAAL, with the NACO observations in the central part.

This contribution gives insight into our preliminary analysis of the deepest and largest near-infrared imaging survey in RCW38. Located in the Vela complex, at a distance of 1.7 kpc, it hosts dozens of OB star candidates. RCW38 is more than twice as dense as the Orion Nebula Cluster and orders of magnitude denser than other nearby SFR.

Previous near-infrared studies of the cluster used data from NAOS-CONICA/VLT and covered about 0.5x0.5 pc in the cluster's core (see Figure 1). The IMF presented in [8] as a power-law with a slope of 0.4±0.2 for low-mass and 1.5±0.1 for massive stars stays in agreement with results for nearby SFRs. Our recent studies obtained by HAWK-I/GRAAL cover a 64 times larger field and contain 20 times more objects, allowing us to study most of the massive cluster (3.7 by 3.7 pc). The 90% completeness limits are J =19.8mag, H = 19.6mag and Ks = 17.7mag as the average values for the full field.

Figure 2 presents the colour-magnitude diagram (CMD) of all the sources detected in the JHK HAWK-I images. One can easily see that substellar objects can be detected at such large distances and substantial extinction.

Using colour-magnitude and colour-colour diagrams, we derived extinction values and masses to the sources in RCW38. Given the young age of the cluster, we expect many sources to host disks or envelops; therefore, we find it necessary to correct for this additional intrinsic excess. The applied correction depends on the position of the star in the J-H vs H-K space. Suppose the star falls in the region where the colours are consistent with reddened evolutionary models. In that case, no correction is applied, extinction and mass are obtained by simple dereddening the source photometry to the isochrone in J vs J-H CMD. If the stars lie inside the colour-colour space attributed to the redder CTTS or Herbig AeBe stars, we deredden them by applying the additional correction. The exact procedure is described in detail in [8].

Confirming a membership of individual sources in our field is not straightforward beside a small fraction of the clearly foreground population that separates nicely on the CMD. The bulk of sources are a mixture of cluster and field members. We, therefore, assess statistically the contamination from background sources by comparing the cluster and control field CMDs. We divided both CMDs into identical grids in both colour and magnitude directions. Next, we calculated the number densities of stars in every cell in each diagram as a sum of individual star's probability, whereas a Gaussian probability distribution represents each star of magnitude and colour, with the widths determined by the uncertainties as shown in [9]. In the last step, cell by cell, the amount of objects associated with the expected control field population is then randomly removed from the cluster CMD. The procedure is repeated for different sizes, and initial positions of the grid result in various membership lists, which were used to estimate uncertainties of the IMF.

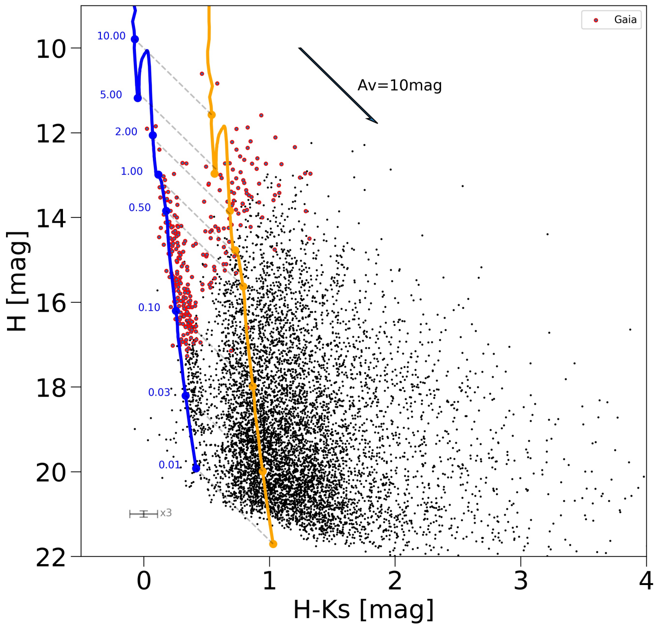

Figure 2: H vs H-Ks color-magnitude diagram of the sources detected towards RCW38. Red dots indicate sources with Gaia parallaxes.The blue solid line shows the 1 Myr isochrone shifted to the distance of 1.7 kpc, the orange line represents the same isochrone reddened to the A_V=10mag. The model masses are marked on the left side of the isochrone, dashed lines indicate corresponding points on the extincted isochrone.

Summary and conclusions

We present the deepest and largest near IR survey in RCW38. We find no clear evidence for variations in the formation efficiency of BDs and very low-mass stars due to the presence of OB stars, or a change in stellar densities. We find the IMF in a form of segmented power law: $\alpha = 0.6 \pm 0.15$ for $M < 0.3\,M_\odot$, and $\alpha = 1.69 \pm 0.18$ for $M > 0.3\,M_\odot$. The star-to-BD ratio (N($\star$)/N(BD) = 2 to 4) also does not seem to depend on neither the stellar density, nor presence of OB stars. A detailed description of our work will be presented in a forthcoming publication (Kubiak et al., in prep.).

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