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The SONYC survey: Towards a complete census of brown dwarfs in star forming regions

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Abstract. SONYC, short for "Substellar Objects in Nearby Young Clusters", is a survey program to provide a census of the substellar population in nearby star forming regions. We have conducted deep optical and near-infrared photometry in five young regions (NGC1333, ρ Ophiuchi, Chamaeleon-I, Upper Sco, and Lupus-3), combined with proper motions, and followed by extensive spectroscopic campaigns with Subaru and VLT, in which we have obtained more than 700 spectra of candidate low-mass objects. We have identified and characterized more than 60 new substellar objects, among them a handful of objects with masses close to, or below the Deuterium burning limit. Through SONYC and surveys by other groups, the substellar IMF is now well characterized down to $\sim 5 - 10\,M_{\rm Jup}$, and we find that the ratio of the number of stars with respect to brown dwarfs lies between 2 and 6. A comprehensive survey of NGC 1333 reveals that, down to $\sim 5\,M_{\rm Jup}$, free-floating objects with planetary masses are 20-50 times less numerous than stars, i.e. their total contribution to the mass budget of the clusters can be neglected.

Key words. Stars: abundances – Stars: formation – Stars: low-mass – Stars: brown dwarfs – Galaxy: star forming regions

1. Introduction

The low-mass end of the Initial Mass Function (IMF) has been the subject of intensive investigation over almost two decades, but the physical processes that set an object's mass in this regime are still matters of debate (e.g. Bonnell et al. 2007; Bastian et al. 2010; Jeffries 2012). Brown dwarfs (BDs) could in theory be produced by various processes, which include dynamical ejections from multiple systems or disks, gravitational fragmentation, and

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photoerosion of cores in the vicinity of OB stars (Whitworth et al. 2007), but their relative importance is not yet clear. Also, deep surveys in star forming regions have revealed a population of objects whose masses are estimated to fall below the Deuterium-burning limit ($\sim 12\,M_{\rm Jup}$), i.e. there seems to be an overlap in the mass space between free-floating objects in clusters, and giant planets. Detailed studies of the substellar mass regime at young ages are therefore crucial to understand the mass dependence in the formation and early evolution of stars and planets.

SONYC - short for *Substellar Objects in Nearby Young Clusters* - is a comprehensive project aiming to provide a complete census of substellar population down to a few Jupiter masses in young star forming regions. By identifying large, unbiased, and well-characterized samples of brown dwarfs in various regions, we can provide the best possible candidates for detailed follow-up studies (e.g. disks, accretion, multiplicity), and try to investigate possible environmental effects. In this contribution we give an overview of all SONYC efforts to date, and summarize the most important results.

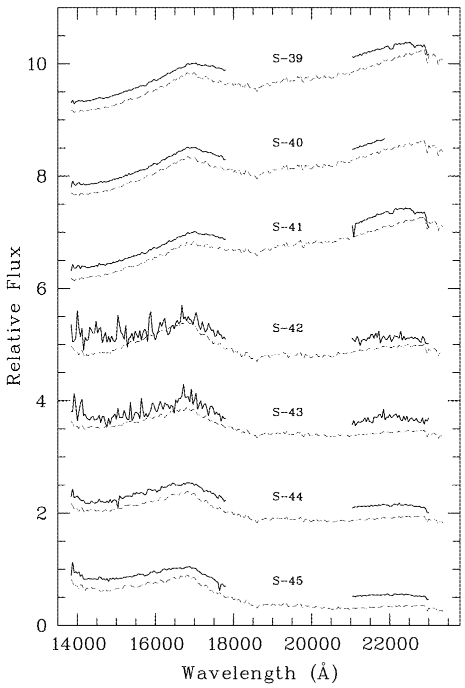

Fig. 1. Near-infrared spectra of the 7 identified very low mass members of NGC1333 (solid lines). The dashed lines show the best-fitting, reddened model spectra. The spectra are offset on the y-axis by constants for clarity. Figure from Scholz et al. (2012b).

2. The SONYC survey

SONYC is designed to reach mass limits well below 0.01 $M_{\odot}$, with the main candidate selection method based on the optical photometry. By detecting the photosphere we ensure we obtain a realistic picture of the substellar population in each of the studied clusters, avoiding the biases introduced by the mid-infrared selection (only objects with disks), or methane-imaging (only T-dwarfs). For the detection of low-mass, pre-main sequence sources, we use our own extremely deep broad-band optical- and near-infrared imaging, in combination with the public photometry catalogues, such as the Two Micron All Sky Survey (2MASS) and the United Kingdom Infrared Digital Sky Survey (UKIDSS). Broad-band selection in regions with significant extinction results in candidate lists with plenty of contamination by embedded stellar members, reddened background M-type stars, and (less likely) late M- and early L-type objects in the foreground. Follow-up spectroscopy is therefore mandatory to confirm the photometric candidates as young very low-mass (VLM) objects. Since in some cases our candidate lists may contain hundreds of objects, the only way to obtain spectra for a large fraction of a sample is by means of multi-objects spectrographs. For this purpose we successfully used MOIRCS (Ichikawa et al. 2006) and FMOS (Kimura et al. 2010) at the Subaru Telescope, and VIMOS (Le Févre et al. 2003) at the ESO's VLT. Other facilities used for the follow-up include SINFONI (Eisenhauer et al. 2003) at the VLT, and SpeX at the IRTF (Rayner et al. 2003). Proper motion analysis can greatly facilitate the candidate selection, and was applied to two of the regions studied so far, Upper Sco and Lupus 3. In Fig. 1 we show MOIRCS spectra of 7 confirmed VLMOs from the latest observing campaign in NGC 1333. Dashed lines show AMES-DUSTY model spectra (Allard et al. 2001) which are used to estimate effective temperatures. As evidence for membership in the near-infrared we use the triangular shape of the water absorption feature in the H-band, typical for young objects later than M3 (Cushing et al. 2005). For the spectra taken at optical wavelengths, we identified M-type objects based on the characteristic molecular bands (mainly TiO and VO; Kirkpatrick et al. 1991), and use several gravity-dependent spectral features, such as Na I absorption at $\sim$ 8200Å.

In the framework of SONYC we have carried out imaging and spectroscopy in five regions (NGC 1333, ρ-Ophiuchus, Chamaeleon-I, Lupus 3, and Upper Scorpius). Our results in Cha I indicate that the current census from Luhman (2007) is mostly complete down to $\sim 8\,M_{\rm Jup}$ and $A_{\rm V} \leq 5$ mag (Mužić et al. 2011). In ρ-Oph we find 10 new VLM sources, and estimate that the number of missing substellar objects in our survey area centered on the main core L1688 is $\sim$ 15, down to $0.003 - 0.03\,M_{\odot}$ and for $A_{\rm V} = 0 - 15$ (Geers et al. 2011; Mužić et al. 2012).

In NGC 1333, a compact cluster in Perseus, we obtained spectra of $\sim$ 80% of all the photometric candidates, making this cluster one of the best studied examples in this scientific field (Scholz et al. 2009, 2012a,b). Among the population of 30-40 spectroscopically confirmed BDs, we find three objects with spectral type $\geq$ M9, i.e. with masses probably lying in the planetary domain. It is in this cluster that we have identified the coolest SONYC brown dwarf. With a spectral type of ~L3, its estimated mass is about $\sim 0.006\,M_{\odot}$, according to the COND (Baraffe et al. 2003) and DUSTY (Chabrier et al. 2000) models. From the HR-diagram for the very low mass population in NGC 1333 shown in Figure 2, it is evident that there is a drop in frequency of observed objects at effective temperatures below 2500 K. As discussed in detail in Scholz et al. (2012b), possible biases of our photometric selection cannot have a major influence on this result, i.e. the drop in the number of the objects in the lowest mass bin appears to be real. This indicates that, down to $\sim 5\,M_{\rm Jup}$, the free-floating objects with planetary masses in NGC 1333 are 20-50 times less numerous than stars.

In a project complementary to SONYC, we have made use of data from the Galactic Cluster Survey, a part of UKIDSS, to search for brown dwarfs in the Upper Scorpius OB association. From the list of high-confidence candidates selected from photometry and proper motions, we obtained 30 spectra and confirmed 24 young very-low mass members of UpSco (Dawson et al. 2011; Dawson et al., in prep). Of these 24, 15-20 are likely to be BDs with masses between 0.01 to $0.08\,M_{\odot}$

In Table 1 we give an overview of the surveyed regions, along with their approximate age and distance, and the area covered by each photometric survey. We also give the completeness levels translated to object mass, by comparison with COND (Baraffe et al. 2003), DUSTY (Chabrier et al. 2000) and BT-Settl (Allard et al. 2011) models. We list the total number of photometric candidates, the number of spectra obtained in the follow-up, and the approximate number of confirmed substellar objects. The main candidate selection is based on optical and near-infrared photometry, and the number of candidates from this selection is given for all the regions. In two cases we also give the number of candidates selected from *Spitzer* mid-infrared data (second number following the plus sign).

3. Brown dwarf frequencies

The ratio of the number of stars to that of BDs has been often used to compare the abundance of substellar objects in different clusters and star forming regions. Here, for the sake of completeness, the low-mass cutoff of the bin representing BDs is set to $0.03\,M_{\odot}$, while the stellar mass bin is set to masses between 0.08 to $1.0\,M_{\odot}$. By compiling the available numbers from the literature, in Scholz et al. (2012a) we have presented tentative evidence for regional differences in the star/BD ratio. The published values range from 2 to 8. At the two extreme values of this range we find two young clusters in the Perseus star forming region, NGC 1333 and IC 348. In NGC 1333, our survey led to a

Table 1. Summary of the SONYC survey

	Cha I	ρ Oph	NGC 1333	Lupus 3	Up Sco
age [Myr]	2	1	1	1	5-10
d [pc]	160	125	300	200	145
area [deg^2]	0.25	0.33	0.25	1.4	57
completeness [$M_\odot$]	0.008	0.003 – 0.03	0.004 – 0.008	0.009 – 0.02	0.02
at A_V	≤ 5	0–15	0 – 5	0 – 5	<5
# of candidates	142	309 + 83	196 + 10	409	96
# of spectra	60	160	160	124	30
# of BDs	~9	~15	30-40	~4	15-20

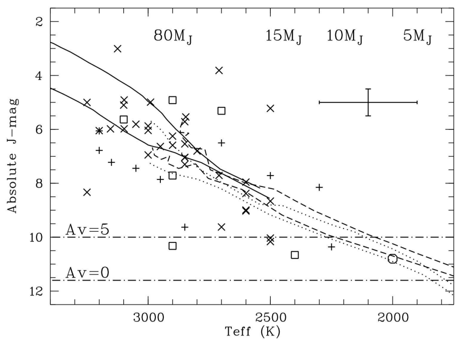

Fig. 2. HR diagram for the very low mass population in NGC1333 (crosses – objects known before in the census of Scholz et al. (2012a), pluses – new objects found in the latter study, squares – new objects identified in Scholz et al. (2012b)). The circle shows the improved parameters for SONYC-NGC1333-36 after fitting the photometric SED. Model isochrones (solid – BCAH, dotted – DUSTY, dashed– COND) are shown for 1 (upper) and 5 (lower) Myr. The dash-dotted lines show the limits of our spectroscopic survey for A_V = 0 and 5 mag.

star/BD ratio of 2, while Luhman et al. (2003) and Andersen et al. (2008) find a ratio of 8 for the slightly older IC 348 cluster. While at face value this might indicate variations in the BD abundance by a factor of 4, the uncertainties in these numbers have not been thoroughly investigated. In our most recent SONYC contribution (Scholz et al., 2013, submitted), we revisit the issue by deriving the star/BD ratio in a consistent manner for the two clusters, and investigate the effects that different assumptions imprint on the results. An important part of this work is a comprehensive evaluation of uncertainties due to sample sizes, isochrones used to derive masses, and cluster parameters such as the assumed distance and age. For NGC 1333 we a find star/BD ratio between 1.9 and 2.4, consistent with our previous work. For IC 348, the ratio is found to be between 2.9 and 4.0, suggesting that the value has been overestimated by the previous studies. For these two samples, we find a typical error of ±1 in star/BD ratios, which can be lowered once we have more accurate age and distance estimates. We find that the star forming process generates about 2.5 – 5 substellar objects per 10 stars, which corresponds to a slope of the power-law mass function of α= 0.7 – 1.0.

4. Summary

SONYC has been an ongoing survey program to provide a substellar population census in nearby star forming regions. Here we summarize the main achievements of the survey:

1. The discovery and characterization of more than 60 new substellar objects, including a handful of objects with masses close to, or below the Deuterium burning limit.
2. Through SONYC and similar surveys by other groups, the substellar IMF is now well characterized down to 5-10 $M_{\rm Jup}$, with the number of BDs per 10 stars constrained to 2.5-5 in clusters. This is presently in disagreement with the results from the field

population, where fewer BDs per star are found.

3. Down to $\sim 5\,M_{\rm Jup}$, free-floating planetary mass objects are observed to be rare, 20-50 times less numerous than stars. This implies that their total contribution to the mass budget of the clusters can be neglected. This is in clear disagreement with results of microlensing surveys (Sumi et al. 2011), which state that free-floating planetary-mass objects are twice as common as stars (see also contribution by J. P. Beaulieu in the current proceedings), and with the study in σ Ori which claims a turnover in the mass function around Deuterium-burning mass limit (contribution of M. R. Zapatero Osorio).
4. One of the goals of SONYC is to provide samples of VLM objects that can be used by the community for different follow-up studies. All the published spectra and photometric catalogs will be available online (`http://browndwarfs.org/sonyc`).

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