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# Luminosity functions of YSO clusters in Sh-2 255, W3 main and NGC 7538 star forming regions

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**Abstract.** We have conducted deep near-infrared surveys of the Sh-2 255, W3 Main and NGC 7538 massive star forming regions using simultaneous observations of the $JHK_s$-band with the near-infrared camera SIRIUS on the UH 88-inch telescope. The near-infrared surveys cover a total area of $\sim$ 72 square arcmin of three regions with 10-$\sigma$ limiting magnitudes of $\sim$ 19.5, 18.4 and 17.3 in $J$, $H$ and $K_s$-band, respectively. Based on the colour-colour and colour-magnitude diagrams and their clustering properties, the candidate young stellar objects are identified and their luminosity functions are constructed in Sh-2 255, W3 Main and NGC 7538. A large number of previously unreported red sources ($H - K > 2$) have also been detected around these regions. We argue that these red stars are most probably pre-main sequence stars with intrinsic colour excesses. The detected young stellar objects show a clear clustering pattern in each region: the Class I-like sources are mostly clustered in molecular cloud region, while the Class II-like sources in or around more evolved optical H II regions. We find that the slopes of the $K_s$-band luminosity functions of Sh-2 255, W3 Main and NGC 7538 are lower than the typical values reported for the young embedded clusters and their stellar populations are primarily composed of low mass pre-main sequence stars. From the slopes of the $K_s$-band luminosity functions, we infer that Sh-2 255, W3 Main and NGC 7538 star forming regions are rather young (age $\leq$ 1 Myr).

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## 1. Introduction

Star formation in our Galaxy takes place in the denser regions of the interstellar medium comprising mainly of the molecular gas and the dust components. The (chronological) evolutionary sequences for the formation of low mass and high mass stars are expected to be entirely different, mainly due to the different time scales involved in various physical phenomena. At present, the low mass star formation is much better understood than the higher mass star formation. A generally accepted paradigm for the low mass star formation exists, which is very successful in explaining most of the observational details. There are several reasons for our poorer understanding about the higher mass star formation, e.g., they are very deeply embedded in dense interstellar clouds; shorter formation timescale; formation in clusters; etc. They also show complex structures since the high mass stars generally form in clusters. From the above it is evident that high angular resolution observations in infrared wavelengths have a great potential in the study of high mass star forming regions of our Galaxy. We have therefore conducted deep near-infrared (NIR) surveys of massive and distant star forming regions, of which the results for the Sh 2-255, W3 Main and NGC 7538 regions are presented in this paper.

Sh 2-255 is the brightest part of a nebula complex (Sharpless 254–258) around IC 2162 in Orion and has a remarkable resemblance to the emission part of the Trifid nebula (M20). The molecular cloud associated with Sharpless 254 through 258 is an active, ongoing star formation location. These regions of ionized gas are at a distance of 2.5 kpc from us. Sh 2-255 region was previously imaged at $K$-band by Hodapp (1994).

W3 giant molecular cloud complex is a well-studied star formation complex located in the Perseus arm at a distance of 1.83 kpc that contains objects such as H II regions, embedded IR sources (including the extremely luminous cluster of sources W3 IRS 5), OH and water masers. Megeath et al. (1996) found a dense concentration of stars in the molecular clump surrounding W3 IRS 5. Their NIR data showed a large, embedded population of intermediate to low mass stars co-existing with recently formed OB stars. They also argued that the formation of high mass stars is associated with the formation of dense clusters of low mass stars in the W3 Main star forming region.

NGC 7538 molecular cloud complex is a well-studied star formation region, which is part of the Cas OB2 complex at a distance of 2.8 kpc that contains objects such as HII region, embedded IR sources (including the extremely luminous cluster of sources NGC 7538 IRS 1–3) and water masers. Among the distant massive star forming regions, NGC 7538 contains rich clusters of young stars (Hodapp, 1994) which have recently been formed. Bloomer et al. (1998) imaged the NGC 7538 IRS 1–3 region in various infrared wavelength bands. They studied in detail the infrared-bright knots due to very young O-type stars (IRS 1, 2 and 3) behind an extinction of at least $A_V = 16$ mag. They found a shell-like structure which presumably corresponds to a shock caused by the high-velocity stellar wind from IRS 2 colliding with the surrounding molecular cloud. The $K_s$-bright source, NGC 7538 IRS 9, was discovered at the tip of the south-eastern nebula and was identified as a protostellar object by Werner et al . (1979).

In this paper we describe the results of our NIR ($JHK_s$) imaging survey of three distant and massive star forming regions: Sh 2-255 (Ojha et al. 2005), W3 Main (Ojha et al. 2004a) and NGC 7538 (Ojha et al. 2004b). Our motivation is to look for new young stellar objects (YSOs) associated with the Sh 2-255, W3 Main and NGC 7538 star forming regions and to classify their evolutionary stages.

## 2. Deep NIR survey of Sh 2-255, W3 Main and NGC 7538

Deep $JHK_s$ simultaneous imaging of the Sh 2-255 ($d$ = 2.5 kpc), W3 Main ($d$ = 1.8 kpc) and NGC 7538 ($d$ = 2.8 kpc) star forming regions were conducted with the SIRIUS (Simultaneous three-colour InfraRed Imager for Unbiased Surveys) camera on the University of Hawaii (UH) 88-inch telescope. SIRIUS is a NIR simultaneous three-band ($J$, $H$, and $K_s$) camera developed jointly by the Nagoya University and the National Astronomical Observatory of Japan (PI: M. Tamura). The design of SIRIUS is optimized to deep and large area surveys in the three NIR bands. It is equipped with three science-grade 1024×1024 HgCdTe arrays manufactured by the Rockwell. The optics is composed of the F conversion lens systems which enables the camera to attach any F10 telescopes, the offner catadioptric system, two dichroic beam splitters and the three standard $JHK_s$ filters. Further details are given in Nagashima et al. (1999) and Nagayama et al. (2003).

Our imaging survey covers a total area of $\sim$ 72 square arcmin with 10-$\sigma$ magnitudes of $J \sim 19.5$, $H \sim 18$ and $K_s \sim 17.3$. We identify more than 4000 NIR sources on the images of the three $K_s$-band surveys. Figure 1 shows the $K_s$-band images of the Sh 2-255, W3 Main and NGC 7538 star forming regions. The individual compact HII regions, Ultra Compact (UC) HII regions and embedded IR sources are marked in the $K_s$-band images.

The $K_s$-band image of W3 Main shows bright nebulosities towards the compact HII regions W3 A, W3 B and W3 D. We also detect a faint nebulosity around the UC HII regions W3 C, W3 E, W3 F and W3 G. W3 H, W3 J and W3 K are more diffuse and dispersed HII regions. The bright massive stars of spectral types O and B are the ionizing sources of the compact and diffuse HII regions (Ojha et al. 2004a). Dark filaments extending from north-west to south-east can be seen between the diffuse nebulosity found throughout the whole image. We see a dense cluster of embedded stars surrounding IRS 5. A large number of red young stars are also seen around IRS 5, which are presumably embedded in the molecular core.

The most prominent features in the $K_s$-band image of NGC 7538 are the diffuse emission to the north-west, the compact and bright emission at the center and the fluffy and dark colour to the south-east. The large diffuse emission extending to north-west of IRS 1, 2 and 3 (see Figure 1) is probably due to the combination of free-free and bound-free emissions, corresponding to what is seen optically and coincides well with the radio brightness. The bright and compact infrared nebula embedded with IRS 1, 2, and 3 at the centre is coincident with the peak of radio continuum (Ojha et al. 2004b). The fluffy nebula associated with IRS 9 is revealed $\sim 2$ arcmin south-east of IRS 1. A few red young stars are located at the easternmost tip of the nebula. The fluffy morphology as well as the dark patches extending $\sim 70$ arcsec to the west plausibly arises from reflection illuminated by these red sources.

A complex of nebulosity is seen in the $K_s$-band image of Sh 2-255. The central cluster of Sh 2-255 contains a large number of infrared bright, reddish, presumably high mass young stars and stellar objects, still embedded in the cloud. A number of OH and $H_20$ masers are also associated with this region, indicating recent and ongoing star formation.

## 3. Young Stellar Objects

Based on the $JHK_s$ colour-colour (CC) and colour-magnitude (CM) diagrams, a rich population of YSOs is identified in the Sh 2-255, W3 Main and NGC 7538 star forming regions besides formerly known YSOs; about 205 YSO candidates in Sh 2-255, 200 in W3 Main and 330 in NGC 7538. These YSOs are classifed into three groups: the Class II-like sources which have NIR excesses that can be explained with the intrinsic colours of T Tauri stars, the Class I or protostar-like sources whose NIR excesses are beyond those of T Tauri stars, and red ($H - K > 2$) sources which seem to be still deeply embedded in molecular cloud cores.

Figure 2 shows the spatial distribution of YSO candidate sources identified in CC and CM diagrams. Spatial distributions of these sources are noteworthy. In Sh 2-255, most of the YSOs are distributed along the molecular cloud region to the north-south. The predominance of red sources in Sh 2-255, their concentration toward north-south and avoidance of YSOs in optical HII regions are quite impressive. It is possible that the older YSOs are presumably associated with the two optical HII regions.

In W3 Main, most of the YSO candidate sources are clusters around the ionized gas of the compact HII regions although the YSOs are more or less distributed all over the field. What is particularly striking is that most of these YSOs are associated with the diffuse ionized gas at the edge of the compact HII regions. Stars with large colour indices ($H - K > 2$) are seen near the dense parts of the molecular cloud. Most of them are clustered near the massive molecular clumps surrounding the luminous infrared sources W3 IRS 4 and W3 IRS 5. Some of them are expected to be members of the embedded stellar cluster around W3 IRS 5.

More interestingly, in NGC 7538, the distributions of three YSO groups are strikingly different: the Class II-like sources are clustered mainly in the optically visible HII region to the north-west, while the Class I-like sources are distributed at the interface between

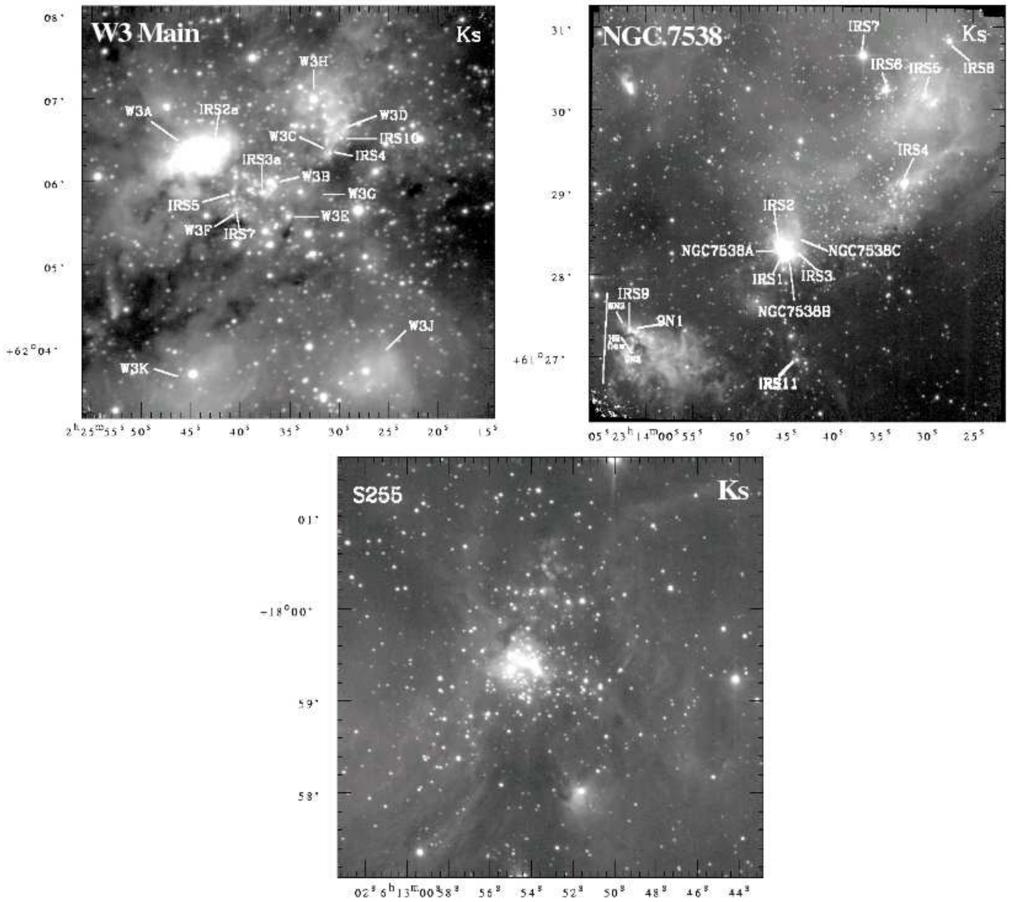


**Figure 1.** $K_s$-band images of the W3 Main, NGC 7538 and Sh 2-255 star forming regions displayed in a logarithmic intensity scale. The field of view is $\sim 4'.9\times4'.9$. The locations of the individual IR sources are marked in the $K_s$-band images. North is up and east is to the left. The abscissa and the ordinate are in J2000 epoch.

the optical HII region and the molecular cloud region to the west. The red sources are clustered in the molecular cloud to the south and south-east. A few red sources are also seen around the ionization front at the interface between the HII region and the molecular cloud, which might have formed due to the triggered star formation.

More detailed discussions are found in Ojha et al. (2004a & 2004b).

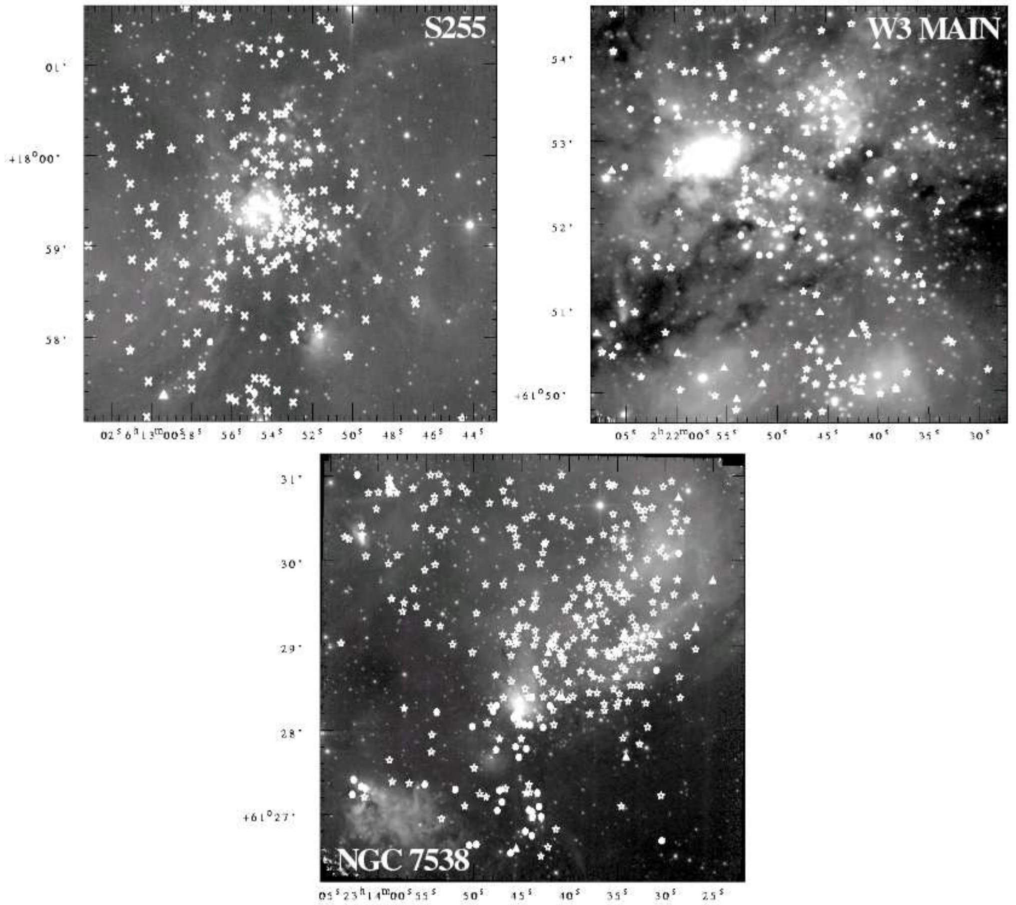


**Figure 2.** Spatial distribution of the YSO colour-excess candidates superposed on the $K_s$-band images of Sh 2-255, W3 Main and NGC 7538 star forming regions, with a logarithmic intensity scale. Asterisks represent T Tauri and related sources (Class II), filled triangles indicate Class I sources, filled circles denote the red sources ($H - K > 2$) and the sources detected in $K_s$-band only (in Sh 2-255) are shown with crosses.

## 4. $K_s$-band Luminosity Function

After correcting for the foreground and background star contamination and photometric completeness, the $K_s$-band luminosity functions (KLFs) were constructed for the Sh 2-255, W3 Main and NGC 7538 regions. The resulting KLFs follow power laws in shape with a slope $\alpha$ [$dN(m_K)/dm_K \propto 10^{\alpha m_K}$, where $N(m_K)$ is the number of stars brighter than $m_K$].

**Table 1.** Power-law fits to KLFs in Sh 2-255, W3 Main and NGC 7538.

| SFR | Sub-region | KLF slope ($\alpha$) |
|---|---|---|
| Sh 2-255 | Cluster | 0.16 – 0.20 |
| W3 Main | W3 IRS 5 cluster | 0.17±0.02 |
| | Whole W3 | 0.26±0.01 |
| | Whole W3 – cluster | 0.28±0.02 |
| NGC 7538 | Younger (IRS 1–3, 9 and 11) | 0.27±0.03 |
| | Whole NGC 7538 | 0.30±0.03 |
| | Older (optical HII) | 0.33±0.04 |

To discuss the relationship between the KLF slopes and the star forming environment of each region, we divided Sh 2-255, W3 Main and NGC 7538 regions into various sub-regions. The derived power-law slopes for the sub-regions of Sh 2-255, W3 Main and NGC 7538 are shown in Table 1. We find that the KLF power law slopes of the Sh 2-255, W3 Main and NGC 7538 are lower than the typical values reported for embedded young clusters (∼0.4, Lada and Lada 2003).

We also find a small increase ($1\sigma$ result, see Table 1) in the KLF slope from the "younger" region to the most evolved "older" region in W3 Main and NGC 7538. This is consistent with an expected change in the KLF slope with age if the IMF is identical in the whole W3 Main and NGC 7538 regions (Megeath et al. 1996). However, such a small effect is not significant in view of the reddening and excess due to circumstellar material. We, therefore, assume a coeval population of stars and derive the KLF of the whole Sh 2-255, W3 Main and NGC 7538 star forming regions for comparison with other regions and a rough estimate of stellar masses in the next section.

Using the analysis as given in detail by Megeath et al. (1996), the estimated KLF slopes of the whole Sh 2-255, W3 Main and NGC 7538 regions are roughly consistent with the Miller-Scalo IMF if the age of Sh 2-255, W3 Main and NGC 7538 population is ∼ 1 Myr.

## 5. Stellar mass estimates

We estimate the mass of the YSO candidate sources from $J$-band luminosity based on recent evolutionary tracks (Palla and Stahler 1999) and assumption of age (e.g., Tamura et al. 1998; Ojha et al. 2004a, 2004b). To estimate the stellar masses, we use the $J$ luminosity rather than that of $H$ or $K_s$, as $J$-band is less affected by the emission from circumstellar materials (Bertout, Basri, and Bouvier 1988).

Using the age of $\sim$ 1 Myr of Sh 2-255, W3 Main and NGC 7538 population, as estimated from the KLF slopes, we find that $\sim$ 80–90% of the YSO candidates have an upper mass limit of 3 $M_{\odot}$. We estimate that the lowest mass limit of Class II and Class I candidates in our observations is 0.1 $M_{\odot}$. Therefore, we conclude that the stellar population in Sh 2-255, W3 Main and NGC 7538 is primarily composed of low mass pre-main-sequence stars.

## 6. Star formation activities in Sh 2-255, W3 Main and NGC 7538

Itoh et al. (2001) presented high-resolution NIR images of the central region of Sh 2-255 obtained with the *Subaru* telescope and an infrared camera, CIAO. Their images clearly resolve two sets of bipolar nebulae illuminated by two independent massive YSOs. Several early B-type stars have been identified in Sh 2-255 region in our NIR survey; some of them are associated with the extended optical HII regions. The location of Sh 2-255, sandwitched between Sh 2-254 and 258 in the ridge of gas observed in CO line emission, indicates that star formation in this region may have been triggered by the expansion of Sh 2-254 and Sh2-257 (Howard, Pipher and Forrest, 1997).

The cluster of compact, ultracompact and hypercompact HII regions embedded within the W3 molecular cloud appears to be ionized by a recently formed association of O and B stars. From our NIR study, it appears that the W3 Main region contains both B stars and lower mass stars, continuously forming. It is generally agreed that W4 (= IC 1805), located to the east of W3, was the first of the three large HII regions (viz. W3, W4, and W5) to be formed and that its expansion might have recently triggered star formation towards the W3 molecular cloud (Elmegreen and Lada 1977). The close association of the embedded clusters with adjacent HII regions also suggests that triggering may have played an important role in the formation of these clusters (Lada and Lada 2003). The W3 GMC is characterized by HII regions, high mass stars, embedded IR clusters and dense molecular cores, and therefore represents an important source for the study of star formation. Compared to, e.g., the Orion Nebula (O'Dell 2001) and M17 (Jiang et al. 2002) regions, one of the prominent features of the star formation in W3 Main is the absence of dominant OB stars.

The NGC 7538 star forming complex seems to be composed of several structures of different evolutionary stages aligned from north-west to south-east. The first is the north-western region, which corresponds to the visible HII region. Here, in addition to the optically visible O-type stars we detect a large number of Class II and Class I sources. Second, a distinct core of star forming activity is found near the centre of our survey area. This is a compact region around IRS 1–3 surrounded by the bright IR nebula. These IR sources are all newly formed OB-star candidates. Together with the ultracompact HII regions that they have started to develop, they are deeply embedded in the dense molecular core. Here we also notice a concentration of red sources. Most probably extensive star forming activity is currently taking place in this region. Turning our eyes farther to the south-east, we find a rather scattered distribution of red sources and Class II candidates. We propose that they compose the third region of star forming activity in the NGC 7538 complex. It seems to be composed of two substructures; one corresponds to the fluffy reflection nebula associated with IRS 9 (the south-eastern region) and the other is the region surrounding IRS 11 and an elongated grouping of red stars (the southern region). This third region, both south-eastern and southern, is located in the molecular cloud and must be very young in terms of star formation.

The central region in NGC 7538 appears to be the result of the propagation of star formation activity from the north-west region due to the expansion of the HII region and the compression of the molecular cloud in the north-western interface. Its location adjacent to the NGC 7538 HII region and the dense concentration of YSOs between the HII region and the IRS 1-3 core match quite well the characteristics of sequential star formation (Elmegreen and Lada 1977). The complex to the south and south-east might have evolved independently from the same molecular cloud. Since this region is separated from the optical HII region of NGC 7538, the star formation here is independent of the action of its expansion and appears to have been taking place spontaneously.

## 7. Conclusions

From the analysis of the deep NIR images presented in this paper, we derive the following conclusions :

i) Based on the NIR CC diagrams and their clustering properties, the candidate YSOs are identified and their luminosity functions are constructed in Sh 2-255, W3 Main and NGC 7538 star forming regions. These YSOs show a clear clustering pattern in each region: the Class I-like sources are mostly clustered in molecular cloud region, while the Class II-like sources in or around more evolved optical HII regions.

ii) In NGC 7538, the YSOs in the central region are probably the result of the propagation of star forming activity from the north-western region due to the expansion of the H II region and the compression of the molecular cloud (sequential star formation, Elmegreen and Lada 1977). The south-eastern/ southern region is independent of the above action and presumably the star formation there is taking place in a spontaneous and gradual process.

iii) In Sh 2-255, W3 Main and NGC 7538, the slopes of the KLFs are lower than the typical values reported for the embedded young clusters. From the slopes of KLFs we infer that the embedded stellar populations are composed of YSOs with an age of $\sim 1$ Myr. Based on the comparison of models of pre-main sequence stars with the observed CM diagram, we find that the stellar populations in Sh 2-255, W3 Main and NGC 7538 are primarily composed of low-mass pre-main sequence stars.

iv) Follow-up deep JHK′ imaging (J $\sim$ 22 mag at 10-$\sigma$) with CISCO/SUBARU 8.2m is planned for the young brown dwarfs search in the cores of Sh 2-255, W3 Main and NGC 7538 regions.

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