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## YOUNG STELLAR OBJECTS IN THE REGION OF DUST BUBBLE N22

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**Abstract.** *The study of young stellar objects is one of the priority areas in modern astrophysics, since these objects serve as key indicators of the processes accompanying the formation of stars and planetary systems. In the process of evolution, especially in the conditions of massive star clusters, they generate intense ultraviolet radiation and stellar winds that are capable to scatter the surrounding matter and forming expanding cavities that are infrared bubble structures in molecular clouds. The study of these structures allows us to obtain valuable information about the mechanisms of interaction of stars with their surrounding environment at various stages of evolutionary development. The aim of this work is to study the region of the dust bubble N22 in order to identify and classify young stellar objects. The main observational material was data obtained by the Wide-Field Infrared Survey Explorer space telescope in the near and mid-infrared range: W1 (3.4  $\mu\text{m}$ ), W2 (4.6  $\mu\text{m}$ ), W3 (12  $\mu\text{m}$ ), and W4 (22  $\mu\text{m}$ ). As a result of the analysis, new candidates for young stellar objects were identified within the studied region: 15 objects belonging to class I, 7 objects - class II, and 13 objects demonstrating the characteristics of transition disks. For all selected candidates for young stellar objects, color diagrams were constructed displaying their position relative to the characteristic regions of the evolutionary stages of young stars. In addition, spectral indices were calculated and the energy distribution in the spectrum was modeled, which confirmed the classification of objects by evolutionary stages.*

**Keywords:** dust bubble, infrared radiation, young stellar objects.

### 1. Introduction

The interstellar medium is the matter and fields that fill the interstellar space within galaxies. The interstellar medium being dynamic and constantly changing, distributed non-uniformly can have different physical and chemical conditions. It consists of hydrogen (about 70%), helium (28%) and heavy elements (2%). In turn, these elements can be neutral or ionized, and can also be collected into molecules. Of all the matter in the interstellar medium, the proportion of atomic ionized matter is 23%, while the proportion of atomic neutral matter is 60%, and the proportion of molecular matter is about 17% [1]. Despite the fact that the interstellar medium is a low-density medium and makes up about 5% of the total mass of stars in the Galaxy, its study is very important for understanding the evolution of the Galaxy. The interstellar medium has everything necessary for the formation of new generations of stars and planets. Stars are formed from interstellar gas, which in the later stages of evolution again give up some of their matter to the interstellar medium. As a result of this exchange, the interstellar medium is enriched with heavy elements created in the

depths of stars. Some of the matter from the interstellar medium is ejected into intergalactic space, and the hot intergalactic gas, with its radiation and pressure, can influence the ionization of the interstellar medium and its dynamics [2]. In our previous studies of the N22 dust bubble [3], Spitzer observations and archival data from the 2MASS, GLIMPSE, and MIPS GAL catalogs were used. Using various classification criteria (L.E. Allen (2004) [4], A. Gutermuth, et al. (2008) [5], and T.P. Robitaille (2008) [6]), around N22 at the early stages of evolution 36 objects were identified that are candidates for young stellar objects (YSOs).

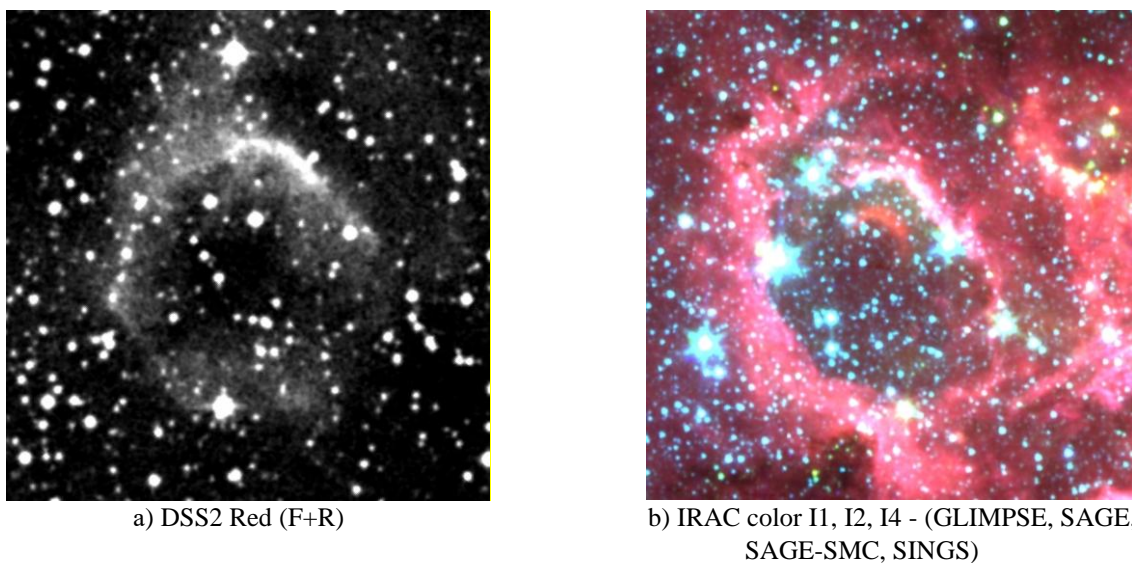
In this paper, in order to identify new candidates and refine the class of previously identified YSOs near the infrared dust bubble N22, we conducted a study using WISE (Wide-Field Infrared Survey Explorer) multi-wavelength observations in the near and mid-infrared range. This choice is due to the fact that in the WISE observation bands, the excess radiation of the cooler circumstellar disk is more significant relative to the stellar photosphere [7].

## 2. Theoretical part

**Data.** In our study we used the astronomical database SIMBAD [8] and data from the VizieR catalog: large-scale infrared observation surveys: 2MASS and AllWISE [9, 10]. In this work we used the 2MASS All-Sky Catalog of Point Sources (2003), a catalog of point sources over the entire sky at a wavelength of two microns. From the catalog we selected observations of the sky in the near infrared range of J (1.25  $\mu\text{m}$ ), H (1.65  $\mu\text{m}$ ), and Ks (2.17  $\mu\text{m}$ ), which were obtained using the 2MASS project.

The AllWISE catalog data in the near and mid-infrared range were obtained by WISE, an infrared space telescope of NASA, using a cryogenic five-mirror afocal telescope with a diameter of 40 cm. The telescope is equipped with four cameras. In the near infrared range, the FWHM is 6.0", and in the mid-infrared range, the FWHM is 12.0". The catalog contains radiation fluxes in the W1 (3.4  $\mu\text{m}$ ), W2 (4.6  $\mu\text{m}$ ), W3 (12  $\mu\text{m}$ ), and W4 (22  $\mu\text{m}$ ) bands. WISE can easily be used as a tool to search for and classify young stellar objects, similar to the work done with Spitzer.

**Infrared dust bubble N22.** N22 (Fig.1) is one of the northern infrared bubbles created by the expanding HII region, an active star-forming region in our Galaxy, catalogued by Churchwell [11]. N22 is a dust bubble centered at Right Ascension (RA;  $\alpha$ )  $\alpha_{2000} = 276.325^{\circ}$ , Declination (Dec;  $\delta$ )  $\delta_{2000} = -13.176^{\circ}$  ( $l = 18.254^{\circ}$ ,  $b = -0.305^{\circ}$ ) with a radius of about 1.77 pc [12]. N22 was also known as an HII region (G18.259-0.307), and its velocity in the hydrogen recombination line  $V_{\text{LSR}}$  is  $\sim 50.9$  km/s, and for the  $V_{\text{CO}}$   $\sim 51.3$  km/s [12]. By comparing with the absorption data of HI G18.259-0.307, the kinematic distance was determined to be  $\sim 4.1 \pm 0.3$  kpc. In the bubble catalog [13], N22 is designated as MWP1G018261-002967. The effective diameter of N22 is 2.09 arcmin, Thickness is 1.88 arcmin, Eccentricity is 0.23, Position Angle is 18 deg.



**Fig.1.** Image of the N22 dust bubble

**Methodology for identification of young stellar objects.** In this work the identification algorithm of X.P. Koenig, et al (2014) [7] was used, which consists of several stages.

*1<sup>st</sup> stage.* In the VizieR catalog from the AllWISE review, when specifying the center point of an object, a search is made for sources within a circle of a certain selected radius. Here, preliminary cleaning is made for flows that have a zero value and which are also unreliable, since they have a measurement error of more than 0.2 mag.

*2<sup>nd</sup> stage.* The previously selected sources need to be cleared of contaminants which also emit in the infrared range. Contamination comes from extragalactic sources such as star-forming galaxies, active galactic nuclei of the broad line (AGN), unresolved knots of shock radiation from outflows colliding with cold cloud material, planetary nebulae, and asymptotic giant branch (AGB) stars (both carbon-rich and oxygen-rich) [14]. To remove contaminants, the criteria described in [15,16] were chosen in this study. Then the sources found in the first stage are tested for the corresponding photometric criteria. In this way, we obtain a list of possible candidates for young stellar objects.

*3<sup>rd</sup> stage.* Firstly, the identification of young stellar objects of class I is performed. Infrared radiation sources for which all conditions are met, according to [7], are recorded as possible candidates for young stellar objects of class I.

*4<sup>th</sup> stage.* Objects that do not meet the conditions of the third stage are tested for compliance with the criteria for young stellar objects of class II (pre-main sequence stars with optically thick disks). Infrared radiation sources for which all photometric criteria from [7] are met are recorded as possible candidates for young stellar objects of class II.

*5<sup>th</sup> stage.* From previously unclassified objects with a non-zero photometric error in the near infrared range according to the 2MASS catalog, according to [7], we separate possible candidates for young stellar objects of classes I and II from young objects of class III and the "transitional disks" class.

*6<sup>th</sup> stage.* Infrared emission objects that do not meet the conditions of the fifth stage are tested against the criteria for young stellar objects of the "transition disk" class. Objects of this class have optically thick excess emission at long wavelengths and virtually no excess at short wavelengths. The remaining objects that do not meet the criteria are classified as class III objects.

*7<sup>th</sup> stage.* At this stage, criteria using the mid-infrared flux - the W4 band (22  $\mu\text{m}$ ) are used. Previously identified objects as AGN candidates are tested to extract possible protostars from them. Infrared emission sources that meet the conditions of [7] are considered as possible protostar candidates.

*8<sup>th</sup> stage.* At the last stage, all possible young stellar object candidates selected at the early stages are retested for new photometric criteria that reveal AGN. Objects for which none of the conditions are met are identified as young stellar object candidates of a previously determined evolution class.

### 3. Results and discussion

The infrared sources of radiation within a radius of 5 arc minutes near the N22 dust bubble were searched (Table 1). A total of 475 objects were detected using the AllWISE survey.

**Table 1.** Parameters for object search

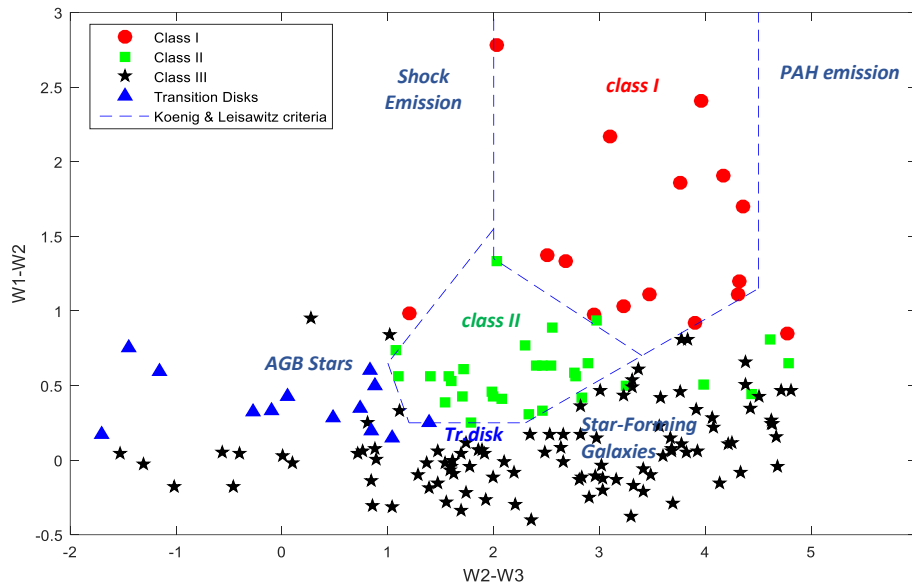
Region	R.A. Range (deg)	Dec. Range (deg)	Search radius (arcmin)	Number of objects found
N22	$276.325 \leq \alpha \leq 276.241$	$-13.176 \leq \delta \leq -13.188$	5	475

The infrared radiation sources with unreliable flux values comprised 115 objects. The criteria of polluting factors were met by 199 objects. Thus, 161 objects were selected for further study. According to the results of the above-described algorithm for testing objects by evolution classes, the following were identified as candidates for young stellar objects: 16 objects of class I, 30 objects of class II, 102 objects of class III and 13 objects of the "transitional disks" class. Figure 2 shows a "color-color" diagram, in which we see that most objects of class I and II lie in the corresponding area of the diagram, according to work [17], except for objects of the "transitional disks" class - they are located on the diagram to the left of the area. Such an arrangement may indicate that for objects of the "transitional disks" class, the photometric properties and the stage of evolution correspond to a later period than for objects of class I and II. Class III objects are already practically formed young stars, therefore their location corresponds to the region of evolution of stellar objects.

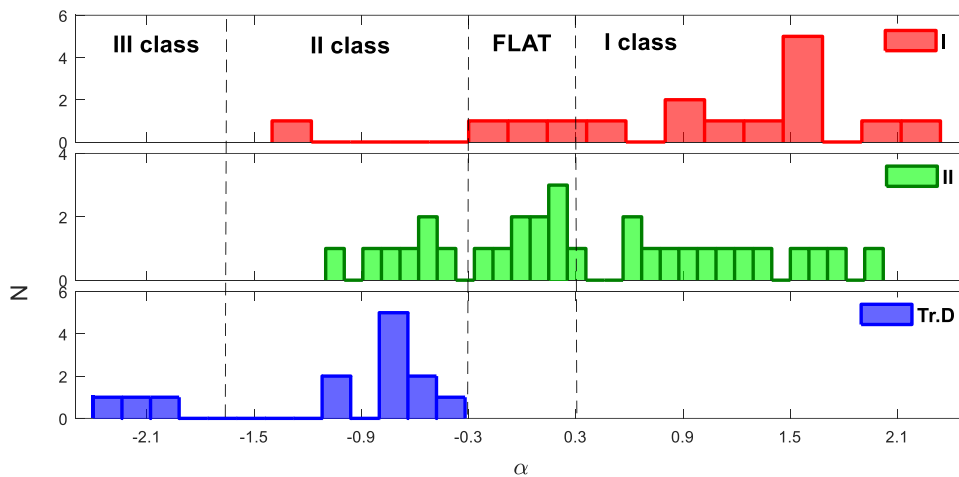
Further, considering that there are currently no unambiguous criteria for identifying young stellar objects, in this work we used several methods to identify true candidates for YSOs. At the next stage of studying the

found YSO candidates, we applied a classification based on the determination of the spectral index, according to [18]. The spectral index is calculated using fluxes in all WISE bands [19]. The distribution of spectral index values by evolution classes is taken in accordance with [20]. We are interested in objects at early evolutionary stages, so further study was carried out only for candidates for I, II, and the "transition disk" class.

Figure 3 shows a diagram showing the quantitative distribution of objects by their spectral index values. For greater clarity, the areas of division by evolutionary stages are shown according to [20].



**Fig.2.** Color-color diagram. Identified candidates for young stellar objects: red squares – class I, green pluses – class II, blue dots – objects with transition disks, black stars – class III



**Fig.3.** Distribution of the number of objects by spectral index

It's shown that for most objects, their distribution corresponds to the evolution classes that were previously determined using the Koenig X. P algorithm [7]. Of the previously identified candidates for class I YSO, 12 objects have the same evolutionary stage and 3 objects have flat spectra. Of the candidates for class II YSO, only 7 objects have the same evolutionary class, and for transition disks, 10 objects belong to class II evolution by spectral index and 3 objects correspond to class III evolution. Taking this into account, we select as candidates for YSO only those objects that belong to the same class in both cases of identification by evolutionary classes. Now we leave 15 objects as candidates for class I YSO, 7 objects as class II and 13 objects as candidates for the "transition disks" class. The candidates for the YSO selected according to two criteria are presented in Table 2.

At the next stage of the research, we searched for information in astronomical catalogues on objects that we identified by two characteristics. Among 15 objects of the class I, 6 objects have already been assigned

the status of young stellar objects: 4\_YSO (2MASS J18252639-1312536 -- Young Stellar Object) [21], 9\_YSO (SPICY 83443 -- Young Stellar Object) [22], 11\_YSO (SPICY 83447 -- Young Stellar Object) [6], 12\_YSO (SSTGLMC G018.2307-00.2427 -- Young Stellar Object) [23], 13\_YSO (SPICY 83414 -- Young Stellar Object) [22, 23], 14\_YSO (2MASS J18252201-1314449 -- Young Stellar Object) [21,23].

**Table 2.** Candidates for the YSO

№	_RAJ2000	_DEJ2000	AllWISE	W1	W2	W3	W4	J	H	K
	h:m:s	d:m:s		mag	mag	mag	mag	mag	mag	mag
Class I										
1_YSO	18 25 12.0	-13 10 15.2	J182512.03-131015.1	10,72	9,69	6,46	2,49	16,69	15,68	13,14
2_YSO	18 25 08.8	-13 08 50.4	J182508.77-130850.3	8,97	7,64	4,96	1,93	17,37	14,97	11,33
3_YSO	18 25 07.4	-13 08 59.5	J182507.35-130859.4	10,26	8,35	4,19	0,73			
4_YSO	18 25 26.4	-13 12 51.9	J182526.41-131251.9	11,86	10,49	7,98	6,26	13,43	13,00	12,57
5_YSO	18 25 07.0	-13 08 59.2	J182507.01-130859.1	10,30	8,44	4,69	1,32			
6_YSO	18 25 06.3	-13 09 05.6	J182506.28-130905.6	10,93	8,52	4,56	1,15	14,77	13,65	13,16
7_YSO	18 25 09.7	-13 07 51.5	J182509.68-130751.5	10,74	9,81	5,91	5,28	16,38	15,65	13,12
8_YSO	18 25 03.8	-13 11 19.3	J182503.83-131119.3	10,01	9,16	4,39	0,89	16,13	14,57	13,29
9_YSO	18 25 04.9	-13 08 47.5	J182504.85-130847.5	13,97	11,81	8,71	2,31	14,85	14,05	14,01
10_YSO	18 25 05.7	-13 08 22.1	J182505.74-130822.1	10,34	7,55	5,52	1,53	16,73	14,38	12,45
11_YSO	18 25 05.4	-13 08 07.1	J182505.38-130807.1	11,92	10,22	5,86	2,50			
12_YSO	18 25 01.8	-13 10 00.8	J182501.84-131000.8	10,25	9,05	4,73	0,16			
13_YSO	18 25 01.0	-13 09 42.6	J182500.98-130942.6	10,54	9,43	5,12	1,48			
14_YSO	18 25 22.1	-13 14 46.3	J182522.07-131446.2	11,45	10,48	7,53	4,94	17,99	16,52	13,62
15_YSO	18 25 06.1	-13 13 47.1	J182506.07-131347.1	10,80	9,69	6,22	2,08	17,36	16,79	13,47
Class II										
16_YSO	18 25 05.9	-13 10 16.4	J182505.88-131016.3	10,05	9,80	8,01	5,53	17,90	14,90	11,95
17_YSO	18 25 24.2	-13 07 30.8	J182524.22-130730.8	8,83	8,41	6,41	3,64	17,08	13,23	10,79
18_YSO	18 25 24.3	-13 07 17.1	J182524.30-130717.1	8,67	8,25	6,54	3,90	15,80	11,80	9,86
19_YSO	18 25 22.5	-13 14 12.8	J182522.54-131412.8	11,27	10,34	7,36	6,60	16,30	15,17	12,89
20_YSO	18 25 29.7	-13 07 19.7	J182529.71-130719.6	11,13	10,72	8,65	6,17	17,99	14,78	12,35
21_YSO	18 25 01.3	-13 12 28.0	J182501.28-131228.0	10,13	9,39	8,32	6,01	13,41	12,13	11,27
22_YSO	18 25 28.2	-13 06 25.2	J182528.20-130625.1	9,16	8,59	7,49	4,54	15,24	12,81	10,61
Transition discs										
23_YSO	18 25 15.0	-13 11 15.2	J182515.03-131115.2	8,542	8,37	10,08	2,62	13,52	11,13	9,92
24_YSO	18 25 11.8	-13 11 54.2	J182511.76-131154.2	10,707	10,11	9,28	4,69	17,34	14,74	12,45
25_YSO	18 25 11.3	-13 12 16.7	J182511.34-131216.7	9,534	9,04	8,16	4,34	17,98	13,28	10,88
26_YSO	18 25 31.0	-13 10 02,0	J182531.00-131001.9	9,461	9,31	8,27	4,64	15,94	12,35	10,59
27_YSO	18 25 20.3	-13 06 58.8	J182520.33-130658.8	10,310	9,56	11,00	8,21	15,48	14,46	12,03
28_YSO	18 25 31.1	-13 08 39.4	J182531.12-130839.3	8,609	8,01	9,18	6,32	18,02	12,79	10,08
29_YSO	18 25 29.5	-13 08 05.8	J182529.54-130805.7	10,818	10,54	10,05	5,76	14,99	12,64	11,57
30_YSO	18 25 28.5	-13 07 17.6	J182528.54-130717.6	8,819	8,49	8,59	6,46	16,09	11,96	9,92
31_YSO	18 25 24.9	-13 06 36.5	J182524.85-130636.4	10,918	10,57	9,84	6,65	13,68	12,81	11,69
32_YSO	18 25 01.1	-13 11 37.8	J182501.14-131137.8	10,472	10,15	10,42	4,75	15,60	14,28	11,93
33_YSO	18 25 31.6	-13 07 18.8	J182531.56-130718.7	10,319	9,89	9,84	5,64	17,60	13,76	11,48
34_YSO	18 25 35.2	-13 08 17.7	J182535.24-130817.7	10,552	10,30	8,92	5,74	17,51	13,46	11,52
35_YSO	18 25 12.5	-13 15 08.5	J182512.53-131508.4	10,842	10,65	9,81	5,55	15,92	14,06	12,10

Among 7 objects-YSO candidates of the class II, 1 object has the YSO status: 21\_YSO (2MASS J18250127-1312279 -- Young Stellar Object Candidate). This object was studied in [22]. Among 13 objects with signs of transition disks, one object, that is 23\_YSO, which is already a formed star 2MASS J18251516-1311139, that is confirmed in [23, 24]. This O-type star is located within the HII region of N22, and was discovered by analyzing radio emission at a wavelength of 20 cm.

The objects in Table 2 with the previously found candidates for YSOs in our work [3]. In the previous study, we studied objects that have infrared fluxes registered by Spitzer were compared. Identification was carried out using the photometric criteria of R. Gutermuth [5]. A total of 36 YSO candidates were identified, information about which is presented in Table 3 of the previous study [3]. Taking into account the fluxes in the near-IR range registered by 2MASS, as well as the coordinates of the sources and their point locations on the integrated maps of the Aladin database, 6 YSO candidates from Table 1 of this study were identified. These are objects No. 15 (4\_YSO), No. 24 (9\_YSO), No. 29 (11\_YSO), No. 32 (12\_YSO), No. 33 (13\_YSO), No. 35 (14\_YSO). As described above, these objects have already been studied and have the status of Young Stellar

Object. Object #2 corresponds to a candidate for a Class III YSO and is presented in astronomical databases as 2MASS J18251320-1310579 -- Young Stellar Object.

Further 10 objects from Table 2 [3] with the initial list of found IR emission objects according to the AllWISE catalog were identified. Objects #6, #9, #11, #13, #21, #25, #26, #28, #31 and #36 were removed at the initial stage of data cleaning because they corresponded to unreliable fluxes in the WISE bands under study. The remaining 19 objects from Table 2 were not reliably identified with the objects found near the N22 bubble.

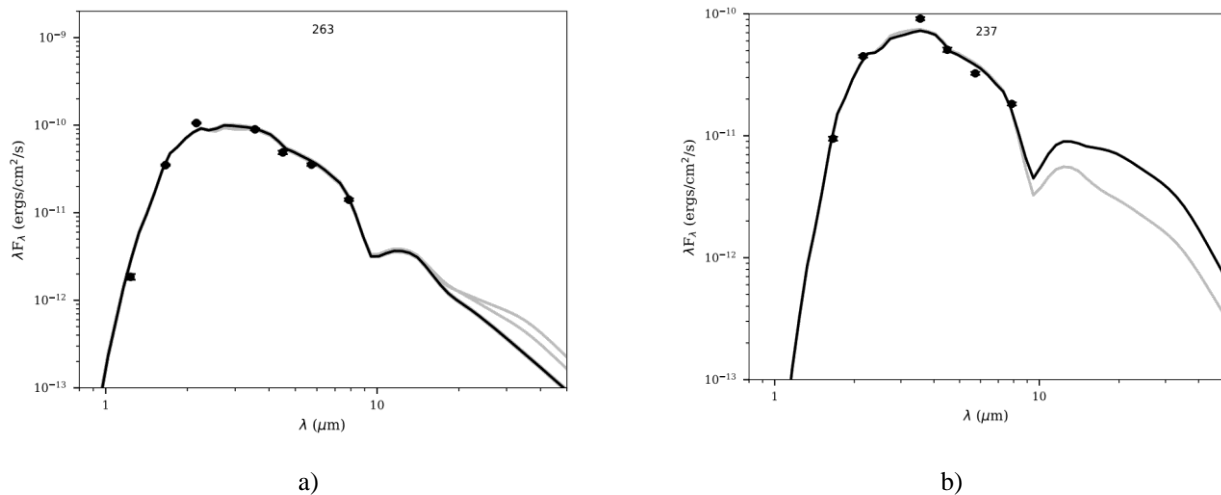
Previously unstudied objects were selected for further study: 9 objects were candidates for class I YSO, 6 objects for class II, and 12 objects for the "transition disk" class.

Spectral energy distributions (SEDs) were constructed for each previously unstudied YSO candidate, and experimental data for the objects under study were fitted to the model data obtained in [25]. This set of models covers a wide range of evolutionary stages of young stellar objects (YSOs), from the youngest, deeply embedded in the envelope of protostars, to stars before the main sequence with small disks or without them.

Figure 4 shows, as an example, the SEDs for YSO candidates 18\_YSO and 17\_YSO (dots) and the models with the smallest standard deviation from the observational data (black line). The best model for the object 18\_YSO is a model without a shell with a disk mass of  $\sim 0.01 M_{\odot}$ , which is typical for a class II YSO. It is also clear from the figure that the parameter

$$\alpha = \frac{d \log(\lambda F_{\lambda})}{d \log(\lambda)}$$

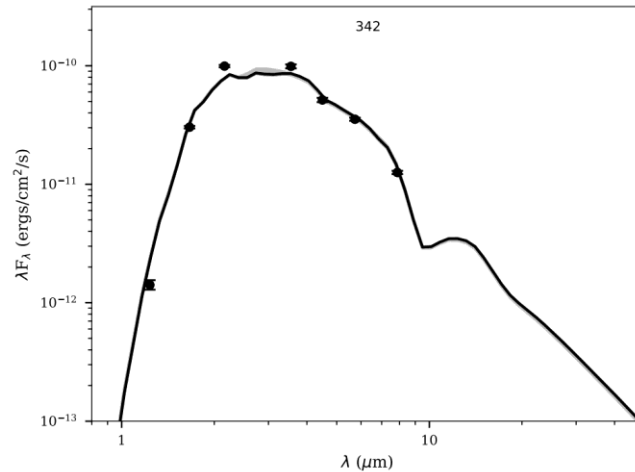
where  $\alpha$  has a value in the range from  $\approx 2$  to  $\approx 10 \mu\text{m}$  that is also characteristic of class II YSOs ( $-1.5 < \alpha < 0$ ).



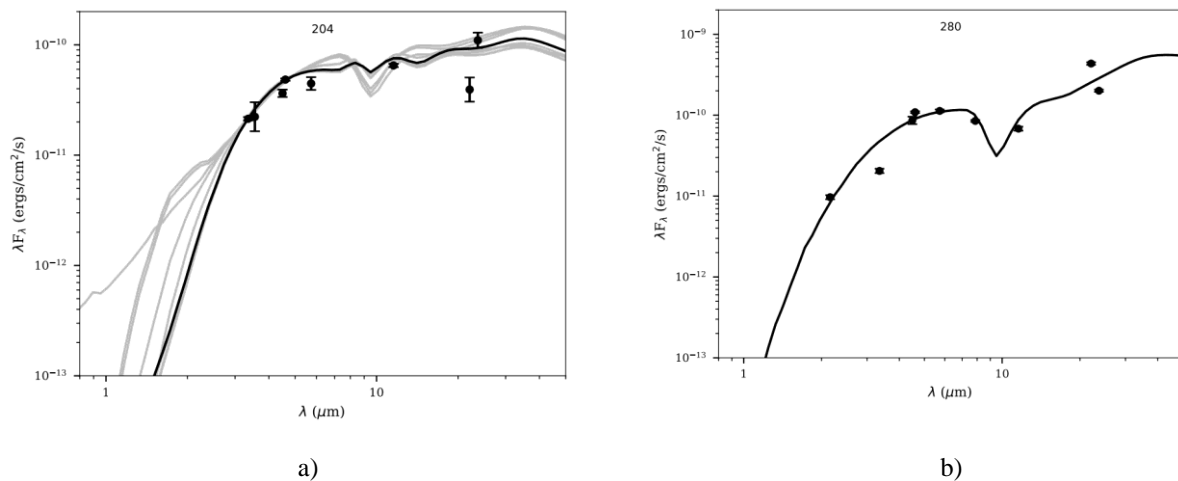
**Fig.4.** Energy distribution in the spectrum of a) 18\_YSO and b) 17\_YSO (dots – observational data, solid line – model [25])

Figure 5 shows an example of a SED for a candidate YSO with a Transition Disk. The best fit for such objects is with models without an envelope with disks of small mass ( $\ll 0.01 M_{\odot}$ ), which corresponds to the generally accepted theory about these objects. Such YSOs are at the stage of transition between a full protoplanetary disk and a scattered disk or already cleared space around a star. The values of the parameter  $\alpha$ , as shown above, also roughly correspond to an intermediate type between Class II and III. The results of model fitting for other objects generally do not contradict the assumption that they belong to the YSO with a Transition Disk type.

As for the class I YSO candidate objects, no data on fluxes at wavelengths  $> 10 \mu\text{m}$  were found for the 2\_YSO object, so we cannot make a definitive judgment about their belonging to a certain class, but fitting the shorter-wave part of the SED classifies them as class II. The situation is similar for the 1\_YSO and 15\_YSO objects, but it should be noted that class I models are also close to their SED. For the remaining objects, fitting the models confirms their belonging to class I (Figure 6).



**Fig.5.** Energy distribution in the spectrum of the object 30\_YSO (dots – observational data, solid line – model [25]).



**Fig.6.** Energy distribution in the spectrum of a) 5\_YSO and b) 10\_YSO (dots – observational data, solid line – model [25]).

#### 4. Conclusion

Using multiwavelength studies and archived catalog data, we studied objects emitting in the infrared range around the N22 dust bubble. The technique includes cleaning the sample from contaminants, identifying objects of classes I, II, III and transition disks. The presented approach to identifying YSOs provides a more reliable classification of them by evolutionary stages.

As a result of the study, infrared objects were selected and classified in the vicinity of the N22 infrared dust bubble based on photometry and spectral index criteria. From the list of 475 initial objects identified within a radius of 5', 161 objects were selected for subsequent analysis. Based on the double identification procedure (by color diagram and spectral index), 35 candidates for young stellar objects were identified: 15 objects of class I, 7 objects of class II and 13 objects with signs of transition disks. Comparison with catalogs made it possible to confirm the status of 7 objects as previously known YSOs.

In addition, their SEDs were analyzed by comparing with the model curves developed in the study, which allowed us to more accurately determine the evolutionary stages of the objects. The results showed that fitting observational data to theoretical models allows us to refine the evolutionary status of some objects, especially for class II objects and those with transition disks. For a number of objects (e.g., 18\_YSO), SED confirm their belonging to class II, both by the shape of the spectrum and by the tilt parameter  $\alpha$ . However, for some objects, the classification remains uncertain due to the lack of photometric data in the far IR range or a high degree of degeneracy of the models. In general, the obtained SED confirm the preliminary classification of most objects

based on photometric criteria and emphasize the need for further observations with higher sensitivity and spectral coverage, especially in the range  $>10\ \mu\text{m}$ , to confidently determine the evolutionary class of YSOs. Thus, the conducted study showed that 27 new young stellar objects in the early stages of evolution were identified around the infrared dust bubble N22.

#### Conflict of interest statement

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

#### CRedit author statement

**Manapbayeva A.B., Alimgazinova N.Sh., Naurzbaeva A.Zh.:** conceptualization, methodology, writing – review and editing; **Kyzgarina M.T., Abildayev N.E., Sarsenbayeva S.N., Turekhanova K.M.:** formal analysis, writing – original draft preparation; **Alibek A.A., Omar A.Zh., Demessinova A.M.:** investigation, validation. The final manuscript was read and approved by all authors.

#### Statement on the use of Artificial Intelligence.

During the preparation of this manuscript, artificial intelligence tools were used solely for language editing and grammatical improvement. No AI tools were used to generate scientific content, analysis, results, or conclusions.

#### Data Availability Statement

The data that support the findings of this article are openly available.

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