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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 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm). 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%) [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. Furthermore, stars are sources of electromagnetic radiation and cosmic rays, which significantly influence the physical state of the interstellar medium [2]. In our previous studies of the N22 dust bubble [3], Spitzer observations and archival data from the 2MASS, GLIMPSE, and MIPSGAL

catalogs were used. In the vicinity of N22, 36 candidate young stellar objects (YSOs) in the early stages of evolution were identified based on various classification criteria [4–6].

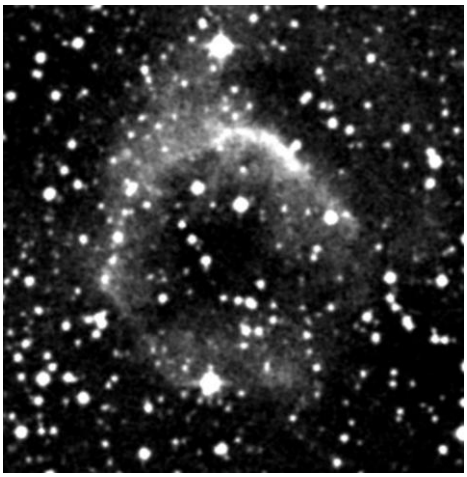
The relevance of the study is determined by the need to clarify the evolutionary stages of young stellar objects in regions of active star formation. The object of this study is the infrared dust bubble N22. The aim of this work is to identify and classify young stellar objects in the region of the dust bubble N22 based on WISE data and archival astronomical catalogs. In this work, we used a comprehensive approach that combined photometric classification using the Koenig & Leisawitz algorithm, spectral index analysis, comparison with astronomical catalogues and modelling of spectral energy distributions (SEDs), which allowed us to identify new candidates for young stellar objects and refine the classification of previously known objects [7].

2. Theoretical part

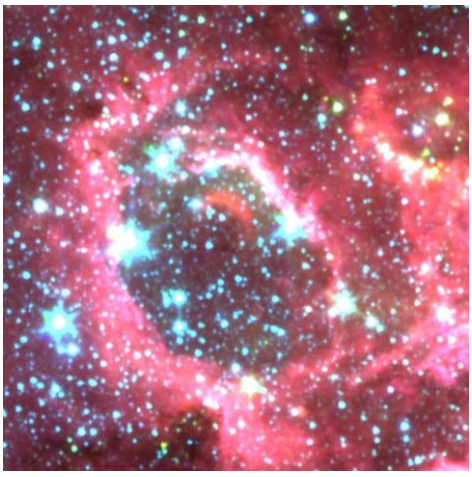
Data. In our study we used the astronomical database SIMBAD [8] and data from the VizieR catalog: large-scale infrared observation surveys: 2MASS and AllWISE [9, 10]. In this work we used the 2MASS All-Sky Catalog of Point Sources (2003), a catalog of point sources over the entire sky at a wavelength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

In this work we used the data from the AllWISE catalog, which contains photometric measurements in the W1 (3.4 μm), W2 (4.6 μm), W3 (12 μm), and W4 (22 μm) bands obtained as part of the Wide-field Infrared Survey Explorer (WISE) survey. Data from these ranges are widely used to search for and classify young stellar objects due to their sensitivity to infrared radiation from circumstellar matter.

Infrared dust bubble N22. N22 is one of the northern infrared bubbles created by the expanding H II region, an active star-forming region in our Galaxy, catalogued [11]. N22 is a dust bubble centered at Right Ascension (RA; α) $\alpha 2000 = 276.325^0$, Declination (Dec; δ) $\delta 2000 = -13.176^0$ ($l = 18.254^0$, $b = -0.305^0$) 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_{LSR} is ∼50.9 km/s, and for the V_{CO} ∼51.3 km/s [12]. By comparing with the absorption data of HI G18.259−0.307, the kinematic distance was determined to be ∼4.1±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.



a) DSS2 Red (F+R)



b) IRAC color I1, I2, I4 - (GLIMPSE, SAGE, SAGE-SMC, SINGS)

Fig.1. Image of the N22 dust bubble

Methodology for the identification of young stellar objects. In this work, the identification algorithm described in [7] was used, which consists of several stages.

1st 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.

2nd 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.

3rd 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.

4th 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.

5th 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.

6th 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.

7th stage. At this stage, criteria using the mid-infrared flux - the W4 band (22 μm) 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.

8th 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≤α≤276.241	-13.176≤δ≤-13.188	5	475

Objects failing to meet photometric quality criteria were sequentially excluded from the initial sample. In the first stage, 115 sources with unreliable measurements (zero flux values or photometric errors greater than 0.2 mag) were removed. This left 360 objects in the sample. In the second stage, 199 contaminating sources were excluded, leaving 161 objects for further classification according to the adopted criteria [7]. Taking this into account, we select as candidates for YSOs only those objects that, in both cases of identification by evolutionary classes, belong to the same class. We now retain 15 objects as candidates for YSOs class I, 7 objects for class II, and 13 objects for the "transitional disk" 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.

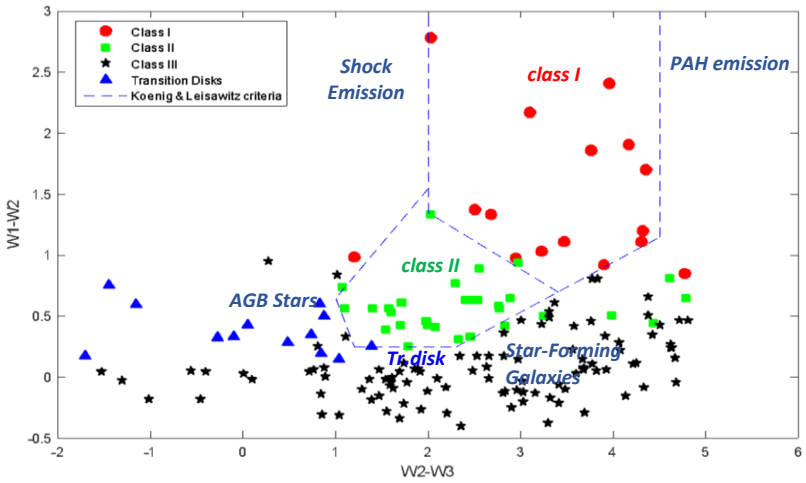


Fig.2. Color-color diagram. Identified candidates for young stellar objects: red squares – class I, green pluses – class II, blue dots – objects with transition disks, black stars – class III

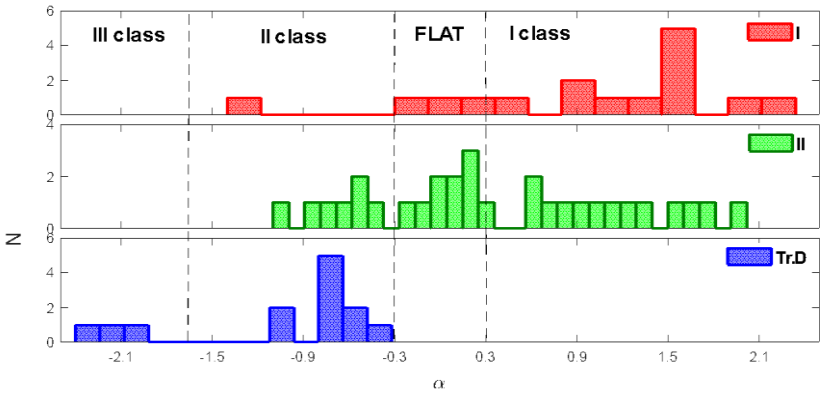


Fig.3. Distribution of the number of objects by spectral index

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].

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 (Application A).

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].

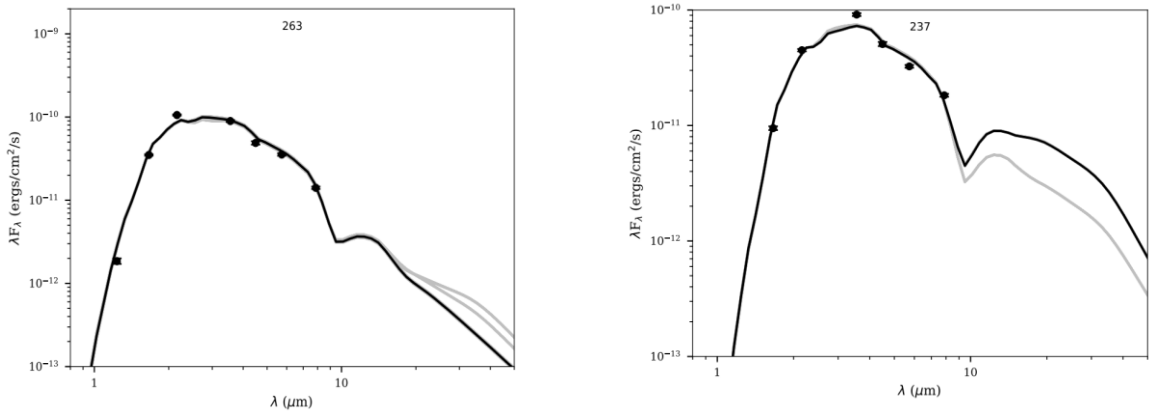
Among 7 objects-YSO candidates of the class II, 1 object has the YSO status: 21_YSO (2MASS J18250127-1312279 -- Young Stellar Object Candidate). This object was studied in [22]. Among 13 objects with signs of transition disks, one object, that is 23_YSO, which is already a formed star 2MASS J18251516-

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.



a) b)

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

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 ~ 0.01 $M_\odot$, which is typical for a class II YSO. It is also clear from the figure that the parameter

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

where α has a value in the range from ≈2 to ≈10 μm that is also characteristic of class II YSOs (-1.5<α<0).

In Figures 4-6, the black curve represents the SED of the best model for the corresponding object, while the gray curves represent the SED of models with standard deviations close to the smallest. Note that for these YSOs, the parameters of model sources with close χ^2 are consistent with the conclusions drawn from the best models.

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 α, 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.

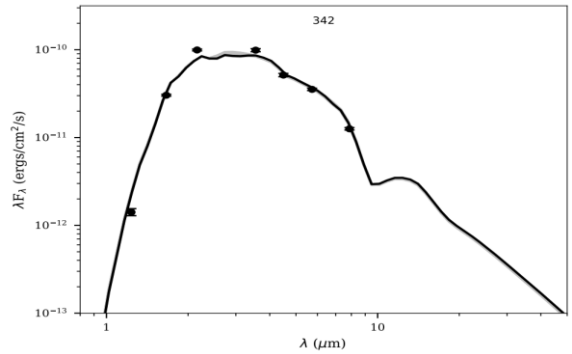
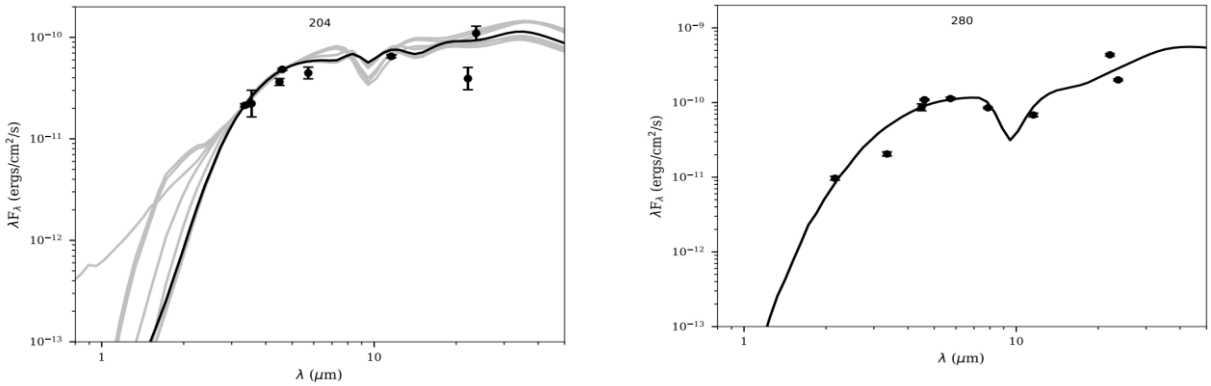


Fig.5. Energy distribution in the spectrum of the object 30_YSO (dots – observational data, solid line – model [25].



a) b)

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

As for the class I YSO candidate objects, no data on fluxes at wavelengths >10 μm 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).

3. Conclusion

Using multiwavelength studies and archived catalog data, we studied objects emitting in the infrared range around the N22 dust bubble. The standard method for identifying young stellar objects used in the study was adapted to study regions of infrared dust bubbles, which made it possible to analyze the N22 region and identify new candidates for young stellar objects.

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, which allowed us to more accurately determine the evolutionary stages of the objects. These 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 α. 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 μm, to confidently determine the evolutionary class of YSOs. Thus, the final classification was based only on objects for which the results of independent identification methods did not contradict each other, which increases the reliability of the resulting classification. The obtained results expand our understanding of the distribution of young stellar objects in the N22 dust bubble region and can be used in further studies of star formation processes in H II regions. It will be advisable to further confirm the classification of the identified candidates using spectroscopic observations and data with higher spatial resolution.

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.: Investigation, Writing - Review and Editing; **Alimgazinova N.Sh.:** Supervision, Methodology; **Naurzbaeva A.Zh.:** Conceptualization; **Kyzgarina M.T.:** Software; **Abildayev N.E.:** Formal analysis; **Sarsenbayeva S.N.:** Writing - Original draft; **Turekhanova K.M.:** Supervision, Project administration; **Alibek A.A.:** Investigation; **Omar A.Zh.:** Software, Visualization; **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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Suplementary materials

Application A

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