TRANSITIONAL YSOS: CANDIDATES FROM FLAT-SPECTRUM IRAS SOURCES

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Abstract

We are searching for Young Stellar Objects (YSOs) near the boundary between protostars and pre-main sequence objects, what we have termed transitional YSOs. We have identified a sample of 125 objects as candidate transitional YSOs on the basis of IRAS colors and optical appearance on DSS images. We find that the majority of our objects are associated with star-forming regions, confirming our expectation that the bulk of these are YSOs.

We present optical, near-IR and high-resolution IRAS images of 92 objects accessible from the northern and 62 from the southern hemisphere. The objects have been classified on the basis of their morphology and spectral index. Of the 125 objects, 28 have a variety of characteristics very similar to other transitional YSOs, while another 22 show some of these characteristics, suggesting that these transitional YSOs are not as rare as predicted by theory.

Key words: Circumstellar Matter – Stars: Formation – Stars: Pre-Main Sequence – ISM: Jets and outflows

1. Introduction

The transition between a Class I and a Class II source (Lada & Wilking 1984) is one of the less well-known phases in the life of a Young Stellar Object (YSO). This period is also one of the most interesting in the evolution of a young star as outflow phenomena, which may determine the final mass of the star and process the material in the surrounding molecular cloud, are particularly active at this stage. However, only few objects are known at or near this boundary between protostar and pre-main sequence star, limiting our possibilities to gain more insight in the physical mechanisms behind this rapid transition. Recently a nebulous object, Holoea (IRAS 05327+3404; Hawaiian for flowing gas), was discovered which shows some characteristics of a Class I source (flat spectrum, outflow), but also has some Class II characteristics (optically visible central star). This object has increased its optical brightness over the last 50 years, suggesting that it is in the process of becoming exposed and making the transition between a protostar and a pre-main sequence star (Magnier et al. 1996, 1999). Guided by the observed properties of Holoea, we have therefore performed a systematic search for additional candidates for the group of transitional YSOs, the results of which are presented in these proceedings.

2. Selection Criteria

Our initial selection criterion for transitional YSO candidates is based on their infrared spectrum. We selected all point sources with infrared colors similar to Holoea ($-1.3 < [12] - [25] = +2.5\log(f_{12}/f_{25}) < -0.40$, $-2.0 < [25] - [60] = +2.5\log(f_{25}/f_{60}) < -1.0$) and reliable data in the 12, 25 and 60 μm bands (Category 3 detections) from the IRAS Point Source Catalog. This resulted in a list of 327 IRAS sources. To narrow down this list, we examined small ($4' \times 4'$) fields extracted from the Digital Sky Survey (DSS) in centered on each source to check for traces of nebulosity, as is also seen near Holoea. Since the nuclei of Seyfert galaxies may have IRAS colors similar to our selected range, a number of sources which were clearly associated with spiral galaxies were also rejected. This resulted in 125 candidate sources. The vast majority of these were found to be located in the vicinity of CO clouds and generally near other signs of active star formation. This lends credence to our suggestion that the bulk of these sources are young stellar objects.

3. Observations

For the southern sources in our list of 125 transitional YSO candidates, CCD imaging in the Bessel V, Bessel R and Gunn i bands was carried out on the Dutch 90cm telescope at ESO, La Silla. For the sources accessible from the north, CCD images of each source in g_*, r_* and i_* (Krisciunas et al. 1998) and near-infrared J, H and K' filters were taken at the University of Washington Apache Point Observatory 3.5m telescope, New Mexico. Data were reduced in a standard fashion, after which they were positionally and flux-calibrated and aperture photometry was performed for the dominant optical source in the IRAS error ellipse. In addition to this, we generated high-resolution IRAS 60 μm maximum entropy processed images (HIRAS; Bontekoe et al. 1994) of the environment of each candidate.

Proc. of 33rd ESLAB Symp. *"Star formation from the small to the large scale"* (F. Favata, A. A. Kaas & A. Wilson eds., ESA SP-445, 2000)

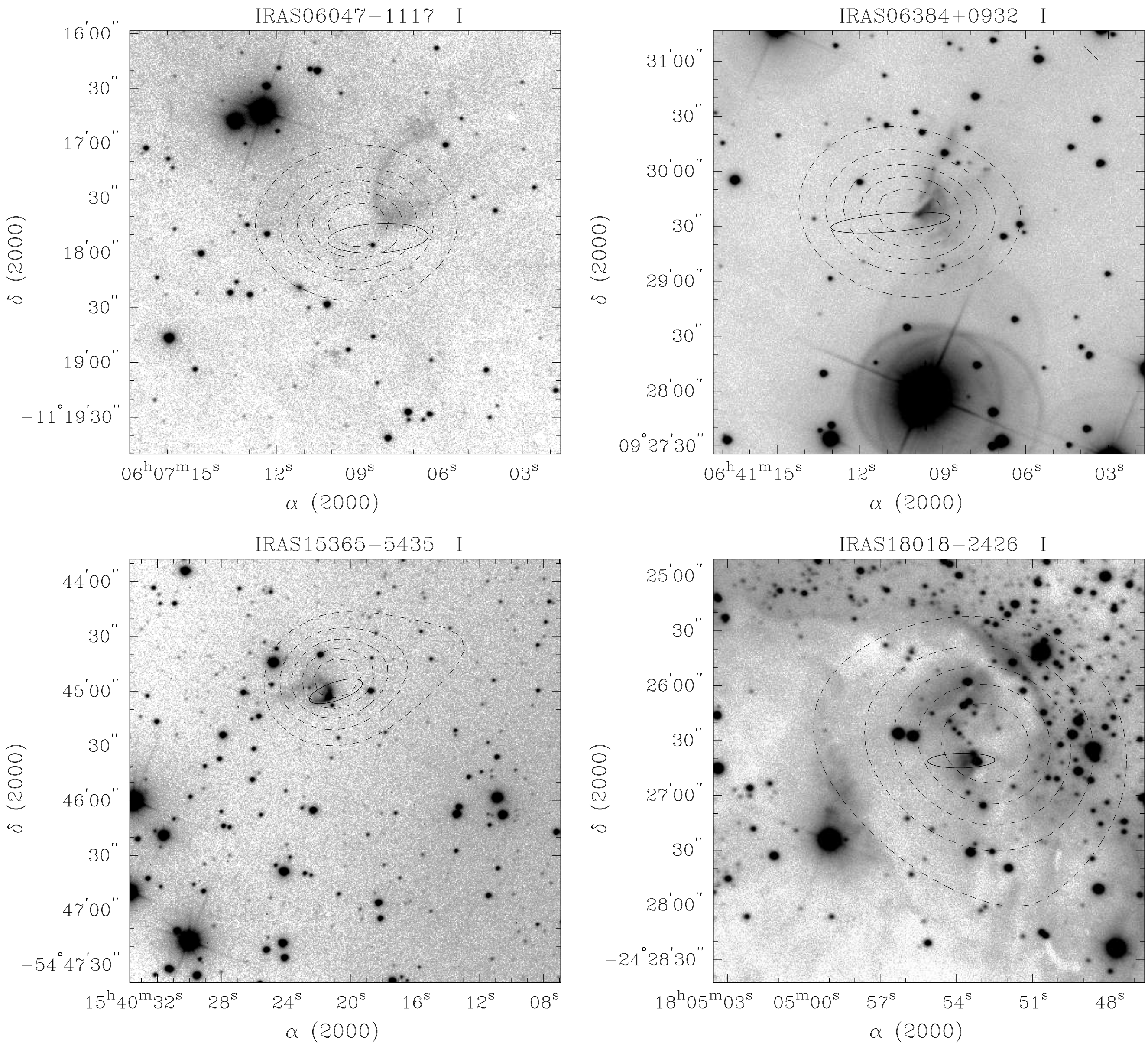

Figure 1. Examples of i band images of southern sources obtained with the Dutch telescope at La Silla. From left to right, top to bottom: IRAS 06047−1117, IRAS 06384+0932, IRAS 15365−5435 and IRAS 18018−2426. Also shown are the error ellipse from the IRAS Point Source Catalogue (solid line) and contours from the HIRAS 60 μm image (dashed lines).

4. Results

We have classified the objects in seven categories based on their morphology in the CCD images and the spectral index of the dominant optical source in the IRAS error ellipse:

1. A likely transitional YSO: A single moderately-bright, very red stellar object with extensive associated reflection nebulosity. (28 objects)
2. A possible transitional YSO: a moderately red stellar object with weak nebulosity or a significantly red object with no nebulosity. (22 objects)
3. A YSO group: Several very red objects, usually with extended nebulosity. No single object stands out. (21 objects)
4. Bright (Herbig Ae/Be like) star. (7 objects)
5. A cluster of stars: usually a red cluster with no single very red star. (18 objects)
6. A galaxy. (11 objects)
7. Nothing: no object stands out, and no object can be associated with any of the other classes. (18 objects)

The sources with Category 1 and 2 classifications (likely transitional YSOs) and Category 4 classifications (Herbig Ae/Be star candidates) are listed in Table 1.

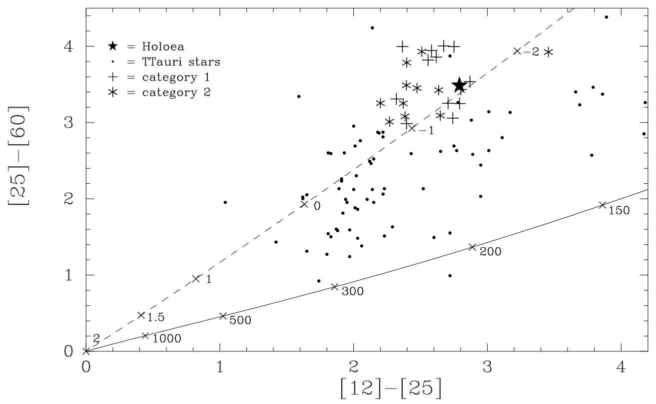

Figure 2. IRAS [12]-[25] vs. [25]-[60] color-color diagram of our category 1 (crosses) and 2 (asterisks) sources. For comparison we also show the location of Holoea (star), the IRAS colors of T Tauri stars in Taurus-Auriga (Kenyon & Hartmann 1995; dots), the location of blackbodies of different temperatures (solid line) and the location of different power-law spectral indices (dashed line).

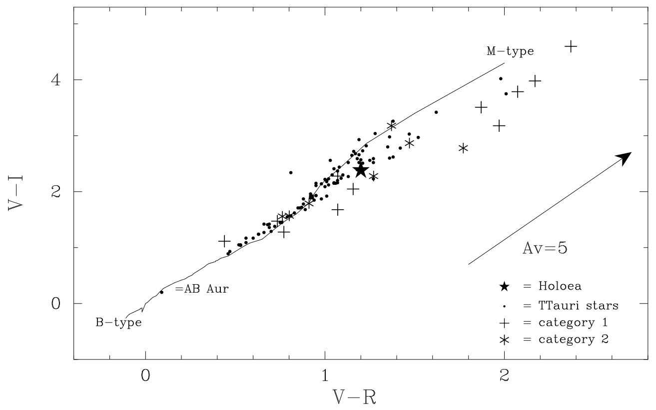

Figure 3. $V-R$ vs $V-I$ color-color diagram of our category 1 (crosses) and 2 (asterisks) sources. For comparison we also show the location of Holoea (star), the colors of T Tauri stars in Taurus-Auriga (Kenyon & Hartmann 1995; dots), and the colors of main sequence stars (solid line). The large arrow shows the direction of normal interstellar reddening.

In Figures 2 and 3 we show infrared and optical color-color diagrams of the sources in our sample with Category 1 and 2 identifications. For comparison we also show the location of T Tauri stars in Taurus-Aurigae, taken from Kenyon & Hartmann (1995) in these diagrams. On average our Category 1 and 2 sources have redder IRAS colors than T Tauri stars. They have an infrared energy distribution that is wider than a blackbody, with a typical peak temperature of 200–300 K. The slope of their energy distribution appears compatible with infall rather than a steady-state disk.

The optical colors of the Category 1 and 2 sources in our sample are on average also redder than those of T Tauri stars. Because the slope of the reddening direction in the $V-R$ versus $V-I$ diagram is nearly parallel to that of decreasing effective temperature, we cannot determine with the current data whether this is caused by a difference in stellar temperature or due to additional extinction in our sources. However, the mere fact that these sources are on average very red suggests that our identification of the optical source with the IRAS source is correct and these objects do indeed have an energy distribution that is similar to Holoea.

5. Conclusions

Our selection criteria to identify transitional YSO candidates have been rather successful. Of the 125 objects, 28 have a variety of characteristics very similar to other transitional YSOs, while another 22 show some of these characteristics. The fact that our Category 1 and Category 2 YSO candidates show on average redder optical and infrared colors than T Tauri stars agrees with our hypothesis that these objects are in the process of making the transition between Lada Class I and II. If confirmed, this would suggest that these transitional YSOs are not as rare as predicted by theory. In addition to this, we have found seven objects to be good candidates for members of the Herbig Ae/Be stellar group, of which three are newly identified as such. A follow-up study of our Category 1, 2 and 4 YSO candidates using newly obtained optical spectroscopy and submillimeter spectral-line data is under way and will allow us to make a more detailed assessment of the nature of these sources.

Acknowledgements

EAM acknowledges support by NWO/Astron under contract number 782-376-011. Support for EAM was also provided by NASA through grant number GO-06459.01-95A from the Space Telescope Science Institute. LBFMW acknowledges financial support through a NWO *Pionier* grant. MvdA acknowledges financial support from NWO grant 614.41.003.

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Table 1. Transitional YSO Candidate IRAS Sources

Category 1 Identifications:

IRAS ID	RA (J2000) DEC	notes
00294+6510	00 32 18.5 +65 27 19	one very red star, bright neighbour, refl. neb.
00353+6249	00 38 17.1 +63 06 01	one very red star, refl. neb.
03260+3111	03 29 10.4 +31 21 58	*in NGC 1333*, very red star, lots of refl. neb.
03383+4343	03 41 44.8 +43 52 54	red star, some neb.
03507+3801	03 54 05.5 +38 10 39	*by refl. neb. PP 11*, red star
04115+5027	04 15 22.2 +50 34 37	very red star, several m. red stars
04553−6921	04 55 05.3 −69 16 55	*in LMC*, some neb., busy field
05327+3404	05 36 05.4 +34 06 11	**Holoea!**, *in M36, NGC 1960*, very red star + refl. neb.
05373+2349	05 40 24.5 +23 50 53	**CPM 19 YSO**,*in KOY98 81* 1 very red star
06047−1117	06 07 08.3 −11 17 51	a very red star + neb. (emis?)
06244+0336	06 27 02.5 +03 34 21	very red star
06567−0350	06 59 14.5 −03 54 51	**BFS 56**,*in FT96 217.4-0.1* very red star, neb.
06568−1154	06 59 13.0 −11 58 56	**CMa West**
06584−0852	07 00 51.6 −08 56 28	**CPM 33 YSO**,*in FT96 221.9-2.0*, red stars, neb.
08211−4158	08 22 52.3 −42 07 56	**HH obj**,*in vdB 15*, refl. neb.
13224−5928	13 25 40.6 −59 43 42	**YSO** ,*in DCld 307.3+02.9*,1 very red star, neb.
14563−6301	15 00 24.9 −63 13 34	*in vdB 65*, 1 red star, neb.
15064−6429	15 10 40.9 −64 40 28	**NGC 5844, PK 317-5.1 PN** Plan. neb.
15365−5435	15 40 21.0 −54 45 00	red star with cometary neb.
17340−3757	17 37 29.6 −37 59 22	very red star, ext. emis. neb.
18018−2426	18 04 53.8 −24 26 40	**RAFGL 2059**, *in M8E region, by S25*, very red star, ext. emis. neb.
20024+3330	20 04 22.5 +33 38 58	**G070.7+01.2 (many IDs)**, Some controversy...
20193+3448	20 21 18.7 +34 57 48	very red star + neb.
20236+4058	20 25 27.8 +41 08 19	*in LBN 253*, very red star + neb.
20337+4036	20 35 32.7 +40 46 33	*in LBN 271*, very red star
20582+7724	20 57 13.1 +77 35 46	*in L 1228*, dark neb., several red obj, neb.
21569+5842	21 58 36.4 +58 57 08	*in L 1143*, very red star, neb.
23395+6358	23 41 56.0 +64 15 09	a single very red star

Category 2 Identifications:

IRAS ID	RA (J2000) DEC	notes
02259+7246	02 30 43.8 +72 59 39	*in L1340*, faint red star, refl. neb.
04020+5017	04 05 47.0 +50 25 07	several (2-3) m. red stars, no obvious neb.
04038+5437	04 07 50.1 +54 45 33	several (2-3) m. red stars, no obvious neb.
04278+2435	04 30 52.7 +24 41 49	**ZZ Tau YSO**, by mol. cl. OMK96 30, 1 m. red star
05223+1908	05 25 16.3 +19 10 45	one red star, some neb.
05343+3605	05 37 41.8 +36 07 20	*by S233, S231*, several m. red stars, 1 very red + neb.
06041+3012	06 07 23.8 +30 11 44	**MWC 790 HAeBe?** 1 very red star, is cluster?
06535+0037	06 56 06.0 +00 33 51	**CPM 31 YSO, ZOAG 212.96+01.29**, m. red star, neb.
07166−1816	07 18 50.8 −18 22 11	some neb.
07183−2741	07 20 21.1 −27 47 02	**Bran 19** ,one red star, some neb.
07221−2544	07 24 13.6 −25 50 03	*in Bran 23* ,one red star, some neb. (emis?)
07254−2259	07 27 35.0 −23 05 25	some neb.
07466−2631	07 48 43.4 −26 39 29	some neb., spike from HD 63599
08404−4033	08 42 17.1 −40 44 10	**ESO Hα 162**,*in BRAN 174*, refl. neb.
08500−4254	08 51 49.2 −43 05 30	*in star forming region?*, red star, some faint neb.
10381−5704	10 40 09.0 −57 20 03	one red star, some neb.
19025+0739	19 04 60.0 +07 44 24	several red stars, no neb.
19050+0524	19 07 32.7 +05 29 41	*by S74*, several m. red stars, dark neb.?
19365+2557	19 38 34.6 +26 04 47	one red star, no neb, globule?
20078+3528	20 09 44.7 +35 37 05	*in LBN 182*, diff. neb, several m. red stars
20172+3554	20 19 10.7 +36 03 54	one very red star, some m. red stars, no neb.
22206+6333	22 22 18.0 +63 48 51	*in L 1204*, some red stars

Category 4 Identifications:

IRAS ID	RA (J2000) DEC	notes
05017+2639	05 04 50.6 +26 43 18	**HD 32509**, bright star, some faint neb. HAeBe?
05293+1701	05 32 14.2 +17 03 25	**HD 36408**, pair of bright stars, highly sat.
06303+1021	06 33 04.4 +10 19 20	**NGC 2247 nebula**, sat in g, i, J, K. neb?
15532−4210	15 56 42.5 −42 19 25	**HD 142527 HAeBe**
18585−3701	19 01 55.3 −36 57 11	**R CrA HAeBe**, *in NGC 6729 dif. neb.*, very lum. refl. neb.
19111+0212	19 13 41.7 +02 17 39	**PK 37-3.3 symb**, bright star
19340+2228	19 36 09.6 +22 35 14	**HD 184961**, bright star