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 \(\mu\)m 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’ × 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 \(\mu\)m maximum entropy processed images (HIRAS; Bonnetoe et al. 1994) of the environment of each candidate.
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 $\mu$m 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.
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 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 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.

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.

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References

Bontekoe, Tj. R., Koper, E., Kester, D.J.M. 1994, A&A 284, 1037
Kenyon, S.J., Hartmann, L. 1995, ApJS 101, 117
Krisciunas, K., Margon, B., Szkody, P. 1998, PASP 110, 753
Lada, C.J., Wilking, B.A. 1984, ApJ 287, 610
Magnier, E.A., Waters, L.B.F.M., Kuan, Y.-J., Chu, Y.-H., Taylor, A.R., Matthews, H.E., Martín, E.L. 1996, A&A 305, 936
Magnier, E.A., Waters, L.B.F.M., Groot, P.J., van den Ancker, M.E., Kuan, Y.-J., Martín, E.L. 1999, A&A 346, 341
| IRAS ID  | RA (J2000) | DEC  |
|----------|------------|------|
| 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. |
| 03833+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+6821 | 04 55 05.3 -89 16 55 | in LMC, some neb., busy field |
| 05327+3404 | 05 36 05.4 +34 06 11 | Holosai, in M36, NGC 1960, very red star + refl. neb. |
| 05373+2349 | 05 40 24.5 +23 50 53 | CPM 19 YSO, in KOY98 #1 very red star |
| 06047+1117 | 06 07 08.3 -13 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 | |
| 06568+1154 | 06 59 13.0 -11 58 56 | CMA West |
| 06854-0852 | 07 00 51.6 -08 56 28 | CPM 33 YSO, in FT96 2291.2-2.0, red stars, neb. |
| 06821-4158 | 08 22 52.3 -42 07 56 | HH obj, in vdB 15, refl. neb. |
| 13247-5028 | 13 25 40.6 -59 43 42 | YSO, in DCM 3073+0291,1 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 49 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 M8 region, by S25, very red star, ext. emis. neb. |
| 20024-5330 | 20 04 22.5 +33 38 58 | G070.7+01.2 (many IDs), Some controversy... |
| 20193+3449 | 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  |
|----------|------------|------|
| 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. |
| 04083+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. OMK63 30, 1 m. red star |
| 05223+1908 | 05 25 16.3 +19 10 45 | one red star, neb. |
| 05343-3065 | 05 37 41.8 -30 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? |
| 06153+0407 | 06 56 06.0 +00 33 51 | CPM 31 YSO, ZOAG 212.96+01.29, m. red star, neb. |
| 07168+1816 | 07 18 50.8 –18 22 11 | some neb. |
| 07183+2741 | 07 20 31.1 –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 Ho 162, in B互AN 174, refl. neb. |
| 08500–4254 | 08 51 49.2 –42 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. |
| 19025–0729 | 19 04 60.0 +07 44 24 | several red stars, no neb. |
| 19050–0924 | 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 |
| 20712–3554 | 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 1294, some red stars |

**Category 4 Identifications:**

| IRAS ID  | RA (J2000) | DEC  |
|----------|------------|------|
| 05017+2639 | 05 04 50.6 +26 43 18 | HD 32509, bright star, some faint neb. HAEBe? |
| 05243+1701 | 05 32 14.4 +17 03 25 | HD 36408, pair of bright stars, highly sat. |
| 06030+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 | 18 51 55.3 –36 57 11 | R CrA HAEBe, in NGC 6729 diff. neb., very lum. refl. neb. |
| 19111–0232 | 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 |