YOUNG STARS IN THE CAMELOPARDALIS DUST AND MOLECULAR CLOUDS. V. MORE YSOs CONFIRMED SPECTROSCOPICALLY

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Abstract. Far red spectra for 22 stars in the Camelopardalis and the northern Perseus dark clouds, suspected to be pre-main-sequence objects (YSOs), are obtained. This evolutionary status is confirmed for ten stars located in the dust and molecular cloud close to the high-mass protostar GL 490, four stars near the H\textsc{ii} region Sh2-205 and one star in the dark cloud TGU 1041. All of these objects exhibit emission in the H\textalpha line and some of them emission in the O\textsc{i} and Ca\textsc{ii} lines. The spectral energy distributions, equivalent widths of the emission lines and approximate spectral classes are determined. Evolutionary stages of the stars are estimated from 2MASS $J$, $H$, $K\textsubscript{s}$, IRAS and MSX infrared photometry. Now we have spectral confirmation of the YSO status for 14 stars in the GL 490 area and 8 stars at Sh2-205. Their spectral types are from A to K, but most of them are either Herbig Ae stars or intermediate objects between T Tauri type and Herbig stars. Both these star forming regions are located near the outer edge of the Local arm at a distance of $\sim 900$ pc.

Key words: stars: pre-main sequence – stars: emission-line – star-forming regions: individual (GL 490, Sh2-205)

1. INTRODUCTION

In the direction of Camelopardalis our line of sight crosses the Local, Perseus and Outer arms. In the two nearest arms numerous dust and molecular clouds with continuing star formation are present, see the review in Stražys & Laugalys (2008b). In the first three papers of this series (Stražys & Laugalys 2007a,b, 2008a, Papers I, II and III) about 200 objects, applying the 2MASS, IRAS and MSX photometry data, were suspected as being pre-main-sequence stars in different stages of evolution. In Paper IV (Corbally & Stražys 2008) the young stellar object (YSO) status was confirmed for 15 brightest stars in this sample – their far-red spectra in the 600–950 nm range exhibit emission lines in H\textalpha, O\textsc{i}, Ca\textsc{ii} and P\textsc{ii}.

About 50 of the suspected YSOs are concentrated in the $3^\circ \times 3^\circ$ area with the
**Table 1.** List of the investigated stars in which emission lines were found. $V$ is the green and $F$ is the red photographic magnitudes taken from GSC 2.3.2 (Lasker et al. 2008). In the last column, YSO means a suspected young stellar object, H$\alpha$ means a star with H$\alpha$ emission found in objective-prism spectra.

| Name   | RA (2000) | DEC (2000) | $\ell$ | $b$  | V   | F   | Type     |
|--------|-----------|------------|--------|------|-----|-----|----------|
| SL 176 | 3 17 24.4 | +57 54 16  | 141.353| +0.351| 14.85| 14.49| YSO      |
| SL 175 | 3 20 53.3 | +58 49 39  | 141.245| +1.375| 13.95| 13.43| YSO      |
| SL 153 | 3 24 27.7 | +57 37 08  | 142.299| +0.619| 18.22| 16.51| YSO      |
| SL 144 | 3 26 20.6 | +58 42 41  | 141.900| +1.666| 17.65| 16.30| YSO      |
| SL 177 | 3 27 58.7 | +58 58 35  | 141.927| +2.004| 17.41| 16.38| YSO      |
| SL 183 | 3 28 47.7 | +57 55 54  | 142.604| +1.201| 14.50| 14.02| YSO      |
| SL 184 | 3 30 03.2 | +58 05 34  | 142.650| +1.428| 18.53| 17.28| YSO      |
| SL 158 | 3 30 05.6 | +58 13 26  | 142.580| +1.539| 15.34| 14.63| YSO      |
| SL 163 | 3 32 53.3 | +58 27 52  | 142.743| +1.946| 18.44| 17.51| YSO      |
| SL 165 | 3 34 00.7 | +58 16 36  | 142.972| +1.878| 15.25| 15.40| YSO      |
| Gahm 4 | 3 45 12.8 | +52 14 38  | 147.849| -2.014| 13.52| 12.76| H$\alpha$|
| Gahm 11| 3 56 14.1 | +52 26 03  | 149.041| -0.809| 13.02| 12.40| H$\alpha$|
| Gahm 24| 3 56 55.2 | +52 51 20  | 148.849| -0.420| 15.08| 14.43| H$\alpha$|
| Gahm 2 | 3 58 13.8 | +52 43 11  | 149.088| -0.396| 14.11| 13.39| H$\alpha$|
| SL 136 | 4 31 52.5 | +49 04 44  | 155.432| +0.635| 15.41| 14.72| YSO      |

center at $\ell$, $b = 142.5^\circ$, $+1.0^\circ$, in the vicinity of the massive protostar GL 490, in the densest part of the dust cloud TGU 942 (Dobashi et al. 2005) located at the outer edge of the Local arm at a distance of $\sim 900$ pc. We decided to verify the evolutionary status of 13 additional stars in this region by new far-red spectral observations. Additionally, we included in the program eight stars in the vicinity of the HII region Sl2-205 located near the Camelopardalis and Perseus border at $\ell$, $b = 148^\circ$, $-1^\circ$ and one star from the catalog of Paper II. The list of the observed stars for which emission-lines were found is presented in Table 1. The stars are designated in the chart with Galactic coordinates in Figure 1, and their identification charts of a $1.8^\prime \times 1.8^\prime$ size are given in Figure 2.

2. SPECTRAL OBSERVATIONS

The spectra were taken on 2008 October 19–21 with the Boller & Chivens spectrograph on the Steward Observatory 2.3 m telescope at Kitt Peak, using the 400 g/mm red-blazed grating, giving a resolution of 5.7 Å and a range from 6070 to 9390 Å on the BCSpec 1200 × 800 CCD detector. The slit width was 1.5$''$.

The spectra, shown in Figure 3 in a widened form, were reduced using IRAF software. 1 An additional step to the reduction procedures followed in Paper IV was to make a far-red fringing correction from blank sky spectra. This had the effect of reducing the H$_2$O and O$_2$ telluric band strengths as well as the fringing.

1 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
Table 2. Equivalent widths of emission lines and spectral classification.

| Star      | Obs. date | EW 6563 | EW 8446 | EW 8498 | EW 8542 | EW 8662 | EW 9226 | Spectral class |
|-----------|-----------|---------|---------|---------|---------|---------|---------|----------------|
| SL 176    | 2008-10-19| −8.3    |         |         |         |         |         | G0e (1)       |
| SL 175    | 2008-10-19| −3.1    |         |         |         |         |         | F0e (0.5)     |
| SL 153    | 2008-10-19| −43.4   | −1.6    | −1.0    |         |         |         | F0e (2)       |
| SL 144    | 2008-10-19| −14.5   | −2.0    | −1.8    |         |         |         | G0e (1)       |
| SL 177    | 2008-10-19| −45.7   | −5.0    | −7.2    | −12.7   | −6.4    |         | A2e (3)       |
| SL 183    | 2008-10-19| −21.7   |         |         |         |         |         | A2e (2)       |
| SL 184*   | 2008-10-21| −24.3   |         |         |         |         |         | F:e (0.5)     |
| SL 158    | 2008-10-19| −17.1   |         |         |         |         |         | A0e (2)       |
| SL 163*   | 2008-10-21| −17.4   |         |         |         |         |         | F:e (0.5)     |
| SL 165    | 2008-10-20| −31.9   | −2.0    | −6.7    | −6.5    | −4.8    |         | G5e (2)       |
| Gahm 4    | 2008-10-20| −38.7   | −2.9    |         |         |         |         | F0e (3)       |
| Gahm 11*  | 2008-10-20| −26.0   | −2.6    |         |         |         |         | F0e (2)       |
| Gahm 24*  | 2008-10-20| −34.5   | −3.1    |         |         |         |         | A5e (2)       |
| Gahm 2*   | 2008-10-20| −61.2   | −4.4    |         | −2.3    |         |         | F0e (3)       |
| SL 136    | 2008-10-21| −39.3   | −4.5    |         |         |         |         | G0e (3)       |
| RY Tau    | 2008-10-19| −11.7   | −1.0    | −2.6    | −1.0    | −1.0    |         | G0e (2)       |
| CW Tau    | 2008-10-19| −243.5  | −8.1    | −30.0   | −24.9   | −25.0   | −4.8    | K5e (3)       |
| DF Tau    | 2008-10-19| −103.1  |         |         |         |         |         | M0e (4)       |
| DG Tau    | 2008-10-21| −79.4   | −2.9    | −30.4   | −20.1   | −28.8   | −3.6    | G:e (5)       |
| DH Tau    | 2008-10-21| −11.1   |         |         |         |         |         | M0e           |

* SL 163 and SL 184: the spectra are very noisy; Gahm 11, 24 and 2: slight nebular emission.

for the low S/N spectra. Detector glitches near 7170 and 8180 Å were also much reduced by this step. The energy distributions, shown in Figure 4 (a–o), were obtained by calibrating the spectra with the spectrophotometric standard Hiltner 600 and removing an atmospheric extinction curve typical for Kitt Peak. For the classification of stars the criteria described by Danks & Dennefeld (1994) in the far-red and near-infrared spectral region were applied. The results of classification are only approximate since the spectral features at this resolution and S/N do not give the discrimination of luminosities and, in some cases, even of spectral subclasses. The emission line intensities of the spectral classifications are scaled in relation to those given by Herbig (1962, Table I) for a few T Tauri stars whose spectra were observed in the same nights as the program stars.

The equivalent widths of the prominent emission features (Hα, Ca II triplet, O I at 8498 Å and P9 at 9226 Å) were measured with the IRAF ‘splot’ utility. They are taken across the whole line, including any absorption wings, so positive EWs will result when there is emission in just the line cores. Since these EW measures rely on a by-eye estimate of the continuum level, three such measures were taken and their mean values are given in Table 2. EWs were measured also in the spectra of five T Tauri stars, RY Tau, CW Tau, DF Tau, DG Tau and DH Tau, having very different emission-line intensities.
3. DESCRIPTION OF INDIVIDUAL OBJECTS

In this section we give more information about the investigated objects and discuss the results of their spectral classification, emission line intensities and spectral energy distribution.

**SL 176 = 2MASS J03172447+5754136 = IRAS 03135+5743**

The object is located at the lower edge of the dust cloud surrounding GL 940. The star can be identified with IRAS 03135+5743 which has reliable flux only in the 25 µm band. This point shows that the SED curve in the \( \log \lambda F_\lambda \) vs \( \log \lambda \) coordinates at \( \lambda > 2 \) µm shows a slow decline typical of YSOs of class II (T Tauri stars). Spectral type (G0e) and the equivalent width of H\( \alpha \) emission (–8.3 Å) given in Table 2 are in agreement with a T Tauri star having a relatively moderate envelope or ring. The emission in lines of O I and Ca II at our resolving power is not detectable. In the \( J-H \) vs. \( H-K_s \) diagram the star lies only \(~0.1\) mag below the intrinsic T Tauri star line (Meyer et al. 1997).

**SL 175 = 2MASS J03205334+5849395**

The object is located in a relatively transparent direction, in the outskirts of the GL 490 cloud, only 101″ from the star HDE 237121 of spectral type B0.5 V, a member of the Cam OB1 association. In the \( J-H \) vs. \( H-K_s \) diagram SL 175 lies about 0.3 mag below the intrinsic T Tauri star line. Our spectrum (F0e) and the faint emission of H\( \alpha \) (\( EW = –3.1 \) Å) are consistent with a post T Tauri or pre-Herbig star on the horizontal radiative track from the T Tauri region to the main sequence (YSO of class III).

**SL 153 = 2MASS J03242757+5737064**

The object is located in the direction of a local dust cloud density enhancement. The star is not present in the IRAS and MSX databases, consequently, we do not know if it has an excess of infrared radiation beyond 2 µm. However, its spectrum exhibits very strong H\( \alpha \) emission (\( EW = –43.4 \) Å) and much fainter emissions in the Ca II triplet. Its spectral type is F0e, and it again may be a pre-Herbig Ae/Be star.

**SL 144 = 2MASS J03262053+5842412**

The object is located in the dust condensation, only 12′ from GL 490. In the \( J-H \) vs. \( H-K_s \) diagram the star lies about 0.2 mag above the intrinsic T Tauri star line. Since the star is absent in the IRAS and MSX databases, we cannot know about the presence of its infrared excess. However, since its spectrum exhibits quite strong H\( \alpha \) line (\( EW = –14.5 \) Å) and Ca II lines, the star is a good candidate for T Tauri stars of spectral class G0e.

**SL 177 = 2MASS J03275850+5858341**

The object is located about 11′ north of GL 490, only 1′ from 2MASS J03275562 +5859269 = IRAS 03239+5849, an infrared and radio source. We classify SL 177 as an A2e star with strong emissions in H\( \alpha \), O I and Ca II, and this is consistent with a Herbig Ae object having a dense disk or envelope. The H\( \alpha \) emission for this star was recently confirmed by the IPHAS survey (Witham et al. 2008; González-Solares et al. 2008).

**SL 183 = 2MASS J03284786+5755560 = IRAS 03248+5745**

The object is located in one of the dust condensations, 0.9° from GL 490. In the \( J-H \) vs. \( H-K_s \) diagram the star lies about 0.3 mag below the intrinsic T Tauri star line, therefore, in Paper III it was suspected to be a Herbig Ae/Be star. The
Fig. 1. Positions of the suspected YSOs in the GL 490 area in the Galactic coordinates. Dust clouds from the Dobashi et al. (2005) atlas are shown in the background. For the stars analyzed in Paper IV and this paper, SL numbers are given. The white circles designate three stars that have no emission lines. The star marked as ‘IRAS’ is IRAS 03243+5819.

Two reliable IRAS points at 12 and 25 \(\mu\)m give much stronger intensity of the star than in the \(JHK_s\) passbands, consequently, the star is an YSO of class I. In our spectrum the \(EW\) of H\(\alpha\) is \(-21.7\) \(\AA\), and the star is of A2e spectral type.

**SL 184 = 2MASS J03300294+5805348 = IRAS 03260+5755**

The object is located in a dust condensation, 0.8° from GL 490. In the \(J–H\) vs. \(H–K_s\) diagram SL 184 lies about 0.3 mag above the intrinsic T Tauri star line. The star has only one reliable measurement in the IRAS passbands, at 25 \(\mu\)m, in which its intensity is comparable with that in \(J, H\) and \(K_s\). Thus, the star belongs to the YSO class II. Our spectrum of this star is very noisy, but it shows a strong H\(\alpha\) with \(EW\) about \(-24.3\) \(\AA\) and spectral type F:e. All the data listed favor the star to be of intermediate type between T Tauri and Ae/Be stars. The presence of emission in H\(\alpha\) was confirmed by the IPHAS survey (Witham et al. 2008; González-Solares et al. 2008).

**SL 158 = 2MASS J03300545+5813253 = IRAS 03261+5803**

The spectrum of this star was first shown in Paper IV. In the \(J–H\) vs. \(H–K_s\) diagram SL 158 lies about 0.15 mag above the intrinsic T Tauri star line. The star has reliable photometry in the IRAS 12 and 25 \(\mu\)m passbands and the MSX
Fig. 2. Identification charts of emission-line stars. The fields of $1.8' \times 1.8'$ size are DSS2 red copies taken from the Internet’s Virtual Telescope SkyView.
Fig. 3. The widened spectra of the investigated emission-line stars. For comparison, the spectra of two T Tauri type stars are given at the bottom. The telluric H$_2$O and O$_2$ bands have not been excluded.
Fig. 4a and 4b. Spectral energy distributions for the stars SL 176 and SL 175.
Fig. 4c and 4d. Spectral energy distributions for the stars SL 153 and SL 144.
Fig. 4e and 4f. Spectral energy distributions for the stars SL 177 and SL 183.
Fig. 4g and 4h. Spectral energy distributions for the stars SL 184 and GL 158.
Fig. 4i and 4j. Spectral energy distributions for the stars SL 163 and SL 165.
Fig. 4k and 4l. Spectral energy distributions for the stars Gahm 4 and Gahm 11.
Fig. 4m and 4n. Spectral energy distributions for the stars Gahm 24 and Gahm 2.
Fig. 4o. Spectral energy distribution for the star SL 136.

8.3 μm passband. Spectral energy distribution shown in Paper III is consistent with an YSO of class III. Our spectrum shows the emission in Hα with EW = −17.1 Å and spectral type A0e. Taking into account changes in the telluric bands, the spectrum is quite similar to that observed in 2007.

**SL 163 = 2MASS J03325315+5827511**

This is the faintest star in our sample, its magnitude $F = 17.51$. Its spectrum is very noisy, and the classification (F: e) uncertain. However, the Hα emission is quite strong ($EW = 17.4$ Å). In the $J−H$ vs. $H−K_s$ diagram it lies exactly on the intrinsic T Tauri star line. The IR source IRAS 03289+5818, located at the 89″ angular distance from SL 163, probably is not related.

**SL 165 = 2MASS J03330073+5816376 = MSX G142.9713+01.8792**

The object in the $J−H$ vs. $H−K_s$ diagram lies about 0.15 mag above the intrinsic T Tauri star line. The MSX flux at 8.3 μm allows us to conclude that the star is an YSO of class II (Paper III). Our spectrum confirms that the star is of T Tauri type with strong emissions in Hα, O I and Ca II; its spectral type is G5e.

**SL 136 = 2MASS J04315244+4904444**

This star is located in the direction of dark cloud TGU 1041 (Dobashi et al. 2005) at the Galactic equator in Perseus. In the $J−H$ vs. $H−K_s$ diagram it lies directly on the intrinsic T Tauri star line. The star is absent in the IRAS and MSX catalogs. Our spectrum of the star shows strong emissions in Hα and O I lines, spectral type G0e. Most probable, it is an YSO of class II.
Table 3. Stars for which our spectra do not show the presence of strong emission lines.

| Name | RA (2000) | DEC (2000) | V   | F   | Sp  |
|------|-----------|------------|-----|-----|-----|
| SL 180 | 3 25 19.2 | +58 11 46  | 15.73 | 15.06 | G8  |
| SL 171* | 3 31 30.2 | +57 21 56 | 18.69 | 16.60 | K3  |
| SL 173 | 3 34 21.2 | +56 43 43 | 14.17 | 13.63 | A5  |
| Gahm 12 | 3 49 06.0 | +51 18 46 | 13.06 | 14.81 | A5  |
| Gahm 3  | 3 54 49.8 | +51 13 37 | 13.98 | 13.43 | A8  |
| Gahm 1  | 4 01 17.5 | +53 10 14 | 11.66 |       | A8  |
| Gahm 26 | 4 01 59.0 | +53 09 44 | 11.53 |       | A8  |

Note: in SL 171 Hα is filled in by emission, i.e., it is a marginal Hα emission star.

The stars Gahm 4 = 2MASS J03451281+5214379, Gahm 11 = 2MASS J03561414+5226030, Gahm 24 = 2MASS J03565522+5251200 and Gahm 2 = 2MASS J03581379+5243109

As was described in Paper I, Gahm (1990) discovered 12 stars with Hα emission in low-dispersion objective-prism spectra located near the Sh2-205 emission nebula. In Paper IV we confirmed the YSO status for four Gahm stars (21, 22, 23 and 25) – three of them were found to fall within the temperature range of T Tauri stars and one to be an Ae-star. More Gahm stars were included in the present investigation and four of them were found to show spectral properties typical of YSOs. All four are probably Herbig Ae stars with strong emissions in Hα and the O I line and spectral types A5e–F0e (Table 2). Since all these stars are absent in the IRAS and MSX catalogs, there was no way to verify their medium infrared energy distributions. Hα emission in two of the investigated stars (Gahm 4 and 11) had been discovered earlier by Gonzalez & Gonzalez (1954). These two stars as well as Gahm 2 are present in the catalog Hα Stars in Northern Milky Way by Kohoutek & Wehmeyer (1997) as KW97 16-16, 16-43 and 16-49, respectively. Recently, Hα emission in Gahm 24 has been found by the IPHAS survey (Witham et al. 2008; González-Solares et al. 2008).

Stars without emission lines

The stars in the spectra of which we did not find emission lines are listed in Table 3. Of them three stars are in the vicinity of GL 490 and four Gahm stars in the vicinity of Sh2-205. The reason is not understood since these stars in the J–H vs. H–K_s diagram lie in the domains of T Tauri and Ae/Be stars. Possibly, some of these stars were misidentified in the finding charts. For example, the star, which we considered as Gahm 1, is located only 70'' south of the known emission line star KW97 16-55. The last column of Table 3 gives spectral classes estimated from our spectra.

4. CONCLUSIONS

The far-red slit spectra of 15 suspected YSOs embedded in dust and molecular clouds of Camelopardalis and the nearby region of Perseus are obtained. Ten of the investigated stars are located in the vicinity of the young stellar object GL 490 in the dark cloud TGU 942, four objects in the vicinity of the H II region Sh2-205 and one object in the dark cloud TGU 1041 in the northern Perseus. All of these objects
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exhibit emission of different intensity in their Hα lines and some of them fainter emission in their OI and CaII lines. The equivalent widths of the emission lines were measured and spectral classes were estimated from the absorption features. To assess the evolutionary status of these stars we made use of their positions in the J–H vs. H–Ks diagram and spectral energy distribution curves in the infrared determined from 2MASS J, H, Ks, IRAS and MSX photometry.

In Fig. 9 of Paper III the color-magnitude diagram Ks vs. H–Ks was plotted for 25 YSOs located in this area, whose pre-main-sequence status was confirmed by IRAS and/or MSX photometry. Now we have spectroscopic confirmation of 14 of these stars (Paper IV and this paper), all brighter than Ks = 11.4. Among these brightest stars of the SFR we have GL 490 (very young YSO of class I), five A-type objects, four F-type objects and four G-type objects. YSOs of types K and M at a distance of 900 pc are probably fainter than the red magnitude F = 17–17.5, the limit of our spectral observations. Among the observed YSOs two are of class I, eight of class II and four of class III.

The comparison of color-magnitude diagrams of the GL 490 and Taurus SFRs (Paper III) leads to the conclusion that YSOs in Camelopardalis are much more massive and younger (of spectral types A to G) than in Taurus. The GL 490 region is also surrounded by the Cam OB1-A association containing tens of O- and early B-stars and some cooler supergiants (Paper I). One of them, HD 21389 (A0Ia), illuminates the reflection nebula vdB 15 in which the GL 490 and other young stars are immersed. In Taurus, YSOs of K and M types dominate, stars of spectral types F and G are very rare, and Herbig A stars are absent. YSOs of types F and G are rare also in other SFRs, even in the young open cluster NGC 2264 which contains the pre-main-sequence of a very broad range of temperatures. According to Cohen & Kuhi (1979), Ho intensities in pre-main-sequence F–G stars vary from zero to $\text{EW} = 55$ Å (LkHα 338 in the Mon R2 region). This is consistent with our results found in the GL 490 region.

Another group of eight confirmed YSOs, discovered by G. Gahm, is related to the SFR close to HII region Sh2-205 near the Camelopardalis and Perseus border at the Galactic longitude 149°. In Paper IV and this paper in this region we have identified YSOs of the following spectral types: two are A-stars, three F-stars, one G-star and two K-stars. Recently, star formation in the region has been investigated by Romero & Cappa (2009) and more YSOs were suspected.

In summary, our spectral observations of suspected YSOs have increased the number of confirmed pre-main-sequence stars in the Camelopardalis dark clouds to 22. The results prove that the dark cloud surrounding a massive protostar GL 490 and the region near the HII cloud Sh2-205 are regions of active formation of stars more massive than the Sun.

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