Herbig Ae/Be Stars toward the Dark Cloud LDN 1667*

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Abstract

We report the discovery of a new emission-line object, named SPH 4-South = (GAIA EDR3 561655330192230272), toward the dark cloud LDN 1667. This object came to our attention after inspecting public images that show a faint diffuse nebula a few arcseconds south of SPH 4, an emission-line object previously classified as a T Tauri star. We present high-resolution spectra and analyzed JHK photometry of SPH 4 and SPH 4-South and new narrowband and archival broadband images of these objects. A comparison of the spectra of SPH 4 and SPH 4-South with high-resolution ones of DG Cir and R Mon strongly suggests that SPH 4 and SPH 4-South are Herbig Ae/Be stars. The classification of SPH 4-South is further supported by using a k-NN algorithm to its position in an H−K versus J−H color-color diagram. Both stars are detected in the four WISE bands and the WISE colors allow us to classify SPH 4 as a Class I and SPH 4-South as a Class II source. We also show that the faint nebula is most probably associated with SPH 4-South. Using published results on LDN 1667 and the Gaia Early Data Release 3, we conclude that SPH 4 is a member of LDN 1667. The case of SPH 4-South is not clear because the determination of its distance and proper motion could be affected by the nebulosity around the star, although membership of SPH 4-South to LDN 1667 cannot be ruled out.

Unified Astronomy Thesaurus concepts: Stellar evolution (1599); Early stellar evolution (434)

1. Introduction

SPH 4 was first discovered as an Hα emission-line object by Schwartz et al. (1990) in the Canis Majoris region and, in particular, toward the dark cloud LDN 1667 (Lynds 1962). This and other 24 emission-line objects were studied using low-resolution spectroscopy by Pereira et al. (2001, hereafter P2001) with the aim of investigating their nature. As a result of that investigation, 16 new Be stars and 7 new T Tauri stars were identified, while two objects failed to show the Hα emission line in the new spectra.

Among the seven stars classified as new T Tauri stars, it was later realized that two of them, SPH 4 and SPH 17, in fact could be Herbig AeBe (HAEBe) stars rather than T Tauri stars. The source of this suspicion was the absence of the H component of the Ca II line in their spectra. This K-H anomaly seems to be a common feature among some HAEBe stars (Herbig et al. 2003) and is due to the presence of the absorption of the P Cygni profile of the H line at 3970.08 Å that obliterates the calcium line at 3968.49 Å. In Figure 1 we illustrate this phenomenon by comparing high-resolution Ultraviolet and Visual Echelle Spectrograph (UVES) spectra of the HAEBe star Z CMa and of the T Tauri star BP Tau. As can be seen in Figure 1, the K and H calcium lines are present in the spectrum of BP Tau, while the H calcium line is absent in the spectrum of Z CMa. In the low-resolution spectra of both SPH 4 and SPH 17 the H calcium line was absent, a fact that was not realized by P2001.

Therefore, during a mission in 2016 March at ESO, SPH 4 was reobserved, this time with high-resolution spectroscopy, to obtain a more precise classification of its nature.

Additionally, inspecting the images of the stellar field in Simbad/Adamin around SPH 4 (already mentioned as Bran 23 by Brand et al. 1986), we noticed a stellar-like object at ~14° southern of SPH 4, that seemed to be surrounded by a faint diffuse nebula. Therefore, we included this object, hereafter called SPH 4-South, in the target list for our spectroscopic observations, and also obtained narrowband optical images of the region around SPH 4 to investigate the faint nebula. The coordinates of SPH 4, and SPH 4-South are given in Table 1 and have been obtained from the Gaia Early Data Release 3 (GEDR 3; Gaia Collaboration et al. 2021).

In this paper, we present the high-resolution spectra of SPH 4 and SPH 4-South and our narrowband and public optical broadband images, and analyze JHK photometry of the two objects. We compare our spectra with high-resolution ones of two well-known HAEBe stars, DG Cir and R Mon, to classify our targets, and discuss the association between SPH 4, SPH 4-South, the faint nebula, and LDN 1667.

2. Observations

The high-resolution spectra of SPH 4 and SPH 4-South were obtained with the Fiberfed Extended Range Optical Spectrograph (FEROS) echelle spectrograph (Kaufer et al. 1999) of the 2.2 m ESO telescope at La Silla (Chile). SPH 4 was observed in the night of 2016 March 23 with an exposure time of 3600 s, while SPH 4-South was observed in the nights of 2016 March 20 and 21, with exposure times of 3600 and 3000 s, respectively. The FEROS spectral resolving power is R = 48,000, corresponding to 2.2 pixels of 15 μm, and the wavelength coverage goes from 4000 to 9200 Å. The spectra were reduced with the MIDAS pipeline reduction package consisting of the following standard steps: CCD bias correction, flat-fielding, spectrum...
extraction, wavelength calibration, correction of barycentric velocity, and spectrum rectification. The spectrum of DG Cir, used as a HAeBe comparison star, was also obtained with the FEROS spectrograph on 2010 May 2. Like the spectra of BP Tau and Z CMa, the spectrum of R Mon used in this study was also obtained with the UVES spectrograph.

Due to the large exposure times, the spectra of SPH 4 and SPH 4-South presented many cosmic-ray events and OH telluric emission lines. We used the FWHM to distinguish cosmic rays from telluric emission lines, and a comparison between spectra of the same object taken at different nights.

For the identification of OH telluric emission lines we used the high-resolution night-sky emission atlas provided by Osterbrock et al. (1996) and Hanuschik (2003).

Narrowband images of the field around SPH 4 and SPH 4-South were obtained on 2017 November 1 with CAFOS at the 2.2 m telescope at the Calar Alto Observatory (Almería, Spain). The detector was a SiTe CCD with 2048 × 2048 pixel² and a plate scale of 0.53 pixel⁻¹. We employed two filters covering the Hα (λ0 = 6580 Å, FWHM = 100 Å) and the [S II] (λ0 = 6700 Å, FWHM = 180 Å) emission lines to obtain images with an exposure time of 2 × 1800 s in each filter. The spatial resolution, mainly determined by the seeing, is ∼2″. The images were cosmic ray cleaned, bias subtracted, and flat fielded using the corresponding tasks in the MIDAS package.

To complete our set of data, we have downloaded the images of the region around SPH 4 and SPH 4-South from the PanSTARRS1 archive (Chambers et al. 2016; Flewelling et al. 2020) in the following filters: g (λ0 = 4881 Å, FWHM = 1256 Å), r (λ0 = 6198 Å, FWHM = 1404 Å), and i (λ0 = 9510 Å, FWHM = 628 Å). These images have a spatial resolution of ∼2″, somewhat better than the narrowband ones.

### 3. Optical Imaging

Figure 2 presents an image of LDN 1667 obtained from the Palomar Observatory Sky Survey (POSS), where the location of SPH 4 and SPH 4-South is indicated and the Hα and [S II] images of the two stars. SPH 4 and SPH 4-South are located toward the west and at ∼12° from the center of the cloud. They are close to bright filamentary structures. The Hα and
images show a faint bipolar nebula with the main axis at PA $\sim 70^\circ$ that crosses SPH 4-South, and unequal lobes with the eastern lobe extending up to $\sim 45''$ and the western lobe up to $\sim 23''$ from the star. Some structure can be recognized in the eastern lobe in the form of two relatively bright regions. Figure 3 presents a color composite image obtained from the $y$, $r$, and $g$ PanSTARRS1 images to show the brightest regions of the nebula. These regions are relatively complex and show a narrow structure toward the NE emanating from the star, bright emission encircling a cavity toward the SW, and a bright knot toward the NW. The images strongly suggest that the faint nebula is associated with SPH 4-South.

As we will see below, the spectra of SPH 4 and SPH 4-South are mainly characterized by emission lines. The fiber size of FEROS is 2'' and was centered on the stars and we have not used an off-source fiber to study the spectrum of the nebula. Therefore, it is important to discuss whether the "stellar" spectra could be contaminated by nebular emission. Emission lines due to $[\text{N II}]$ and, perhaps, $[\text{S II}]$ are present in the stellar spectra and could have a nebular origin. Balmer lines ($\text{H}\alpha$ and $\text{H}\beta$) are strong and present a P Cygni profile typical of young stars. Other emission lines due to $\text{FeII}$ or $\text{MgI}$ (see below) are relatively strong, in many cases stronger than the $[\text{N II}]$ emission lines. These emission lines are very faint (if detected) in nebulae associated with young stars, and in addition, they are not expected from the detected nebula given its faintness. Thus, we conclude that contamination of the stellar spectra by nebular emission lines has no influence in the analysis and in the classification of the stars.

4. Line Identification and the Nature of SPH 4 and SPH 4-South

Figures 4–6 shows portions of the spectra of SPH 4 and/or SPH 4-South together with spectra of R Mon and/or DG Cir that have been used as comparisons to investigate the nature of the two emission-line stars. Figures 9–22 (in Appendix) show additional spectral regions.

Table 2 lists the observed wavelength, the FWHM, the equivalent width of the identified emission lines, the line identification, whenever possible, and the number of the figure showing the spectra. For some emission lines, such as $\text{H}\alpha$...
Figure 4. Normalized spectra of SPH 4 (FEROS) and DG Cir (UVES and XShooter). Notice the absence of the H calcium emission line in both stars and the broad absorption due the H$_r$ line.

(Figure 6), H$\beta$ (Figure 9), the sodium lines (Figure 16), and [O I] at 6300 Å (Figure 18), we do not provide the equivalent width and the FWHM due to their observed complex profiles. Additionally, the emission line profiles of these lines are affected by circumstellar absorption and/or emission as well as by telluric absorption and/or emission. We note that very faint [N II] and, perhaps, [S II] emission lines are detected in both stars (Figure 6).

SPH 4 presents a rich emission line spectrum, mainly due to Fe II lines, as earlier shown in the low-resolution spectra presented by P2001. The spectrum of this star shows remarkable similarities with that of DG Cir, as can be recognized in the figures. Particularly noticeable is the absence of the H calcium line, which is in agreement with that observed in DG Cir and other HAeBe stars (Figures 1 and 4). The Balmer emission lines H$\beta$ and H$\alpha$ present a P Cygni profile that is very similar to that observed in DG Cir. From these similarities we conclude that SPH 4 is a HAeBe star, rather than a T Tauri star. SPH 4-South does not exhibit a rich emission-line spectrum. In general, the spectrum of SPH 4-South is similar to that of R Mon, although we did not detected any emission in the region of the H and K calcium lines. The spectra suggest that SPH 4-South may also be a HAeBe star. Alike SPH 4 and DG Cir, R Mon is considered as a “continuum star” by Hernández et al. (2004) due to a high nonphotospheric continuum veiling and, hence, the absence of some photospheric absorption lines. A similar classification may hold from SPH 4-South. Yet, a few absorption lines could be identified such as Mg I at 5183.62 Å in the spectrum of SPH 4, (Figure 12), K I at 7698.98 Å in the spectra of SPH 4 and SPH 4-South, and the oxygen triplet at 7771−7775 Å in the spectra of SPH 4-South and R Mon (Figure 5).

From well-defined emission lines, we obtain (LSR) radial velocities of $+15.2 \pm 1.3$ and $−32.3 \pm 0.9$ km s$^{-1}$ for SPH 4 and SPH 4-South, respectively. We have tried to measure the stellar velocity from the few observed absorption lines, but the faintness or broadening of these lines does not provide reliable results.

5. SPH 4 and SPH 4-South in the $H−K$ versus $J−H$ Diagram and in the WISE Bands

In Figure 7 we examine the positions of SPH 4 and SPH 4-South in the $H−K$ versus $J−H$ diagram based on data given in Table 3 and compare them with a sample of T Tauri and HAeBe stars. In addition, we also insert in the diagram the objects classified as T Tauri stars by P2001. Based on the infrared diagram, it is difficult to classify SPH 4 and SPH 4-
South either as a HAeBe or T Tauri star since they both lie in between the region occupied by these two groups of stars. SPH 17, previously classified as a T Tauri star by P2001, occupies the region of HAeBe objects. In fact, inspecting the low-resolution spectrum of SPH 17 (see P2001), we see that it is very similar to the low-resolution spectrum of SPH 4 and, in addition, the H calcium line is absent (see above). Therefore, we reclassify SPH 17 as a HAeBe star. The other pre-main-sequence stars SPH 1, SPH 6, SPH 21, SPH 22, and SPH 24, only analyzed with low-resolution spectroscopy, may still be considered candidate T Tauri stars, although some of them lie in between the region occupied by the HAeBe and T Tauri stars.

Figure 8 presents another version of the $H−K$ versus $J−H$ color–color diagram. To gain insight into the classification of SPH4 and SPH4-South, we computed a decision surface around their locations using a $k$-NN algorithm. With this method, each point of the $(H−K, J−H)$ plane was classified as a T Tauri or HAeBe star, based on the most common classification of its $k$-nearest neighbors. Using cross-validation in our data set, we found that $k=25$ was the optimal value.

Overall, the T Tauri and HAeBe stars were well separated. SPH4-South is on the HAeBe side and SPH4 falls very close to the frontier between T Tauri and HAeBe stars. A definitive classification for the objects close to the frontier is hard to establish because there is some overlap in the observed colors. Without the additional information provided by their spectra, their classification is risky. Nevertheless, Figure 8 at least indicates that the classification of SPH4-South as a HAeBe star is indeed statistically possible.

The accuracy achieved with the $k$-NN method was high. The number of misclassified T Tauri stars is 26, which is only about 6% of the total T Tauri sample. For the HAeBe stars, there were 14 misclassifications, which is about 7% of the HAeBe sample. In Figure 8, each of these objects are on the wrong side of the computed frontier. We also display in Figure 8 the error bars for the $H−K$ and $J−H$ colors of SPH4 and SPH4-South, computed from individual magnitude errors. The error bars for SPH4 are relatively small and barely cross the frontier. Analogously, SPH 4-South remains on the HAeBe side, despite the larger color uncertainties.

To further investigate the nature of the two stars, we have followed the method by Fischer et al. (2016) who used the
Wide-field Infrared Survey Explorer (WISE) and the W1−W2 and W2−W3 colors to classify Class I and Class II sources in the Canis Majoris region (see also Lada 1987). Table 4 lists the WISE magnitudes of the two stars that are detected in the four bands, SPH 4 being particularly bright in W4. According to Figure 2 in Fischer et al. (2016), SPH 4 may be classified as a Class I source and SPH 4-South as a Class II one. The infrared emission of Class I sources is dominated by a dusty circumstellar envelope, while a dusty disk dominates the infrared emission of Class II sources that are expected to be more evolved than Class I ones.

6. The Relationship among SPH 4, SPH 4-South, and LDN 1667

As already mentioned, SPH 4 and SPH 4-South are observed toward the dark cloud LDN 1667, and it is interesting to investigate their possible membership to this cloud.

LDN 1667 has not been studied in detail. May et al. (2005, hereafter MGA05) mapped several molecular clouds toward the Pupis–Canis Majoris region using the $^{13}$CO($J = 1-0$) line. SPH 4 and SPH 4-South are observed toward the B molecular cloud identified by MGA05 at $l \sim 239.63$ and $b \sim -4.63$ that coincide with those of LDN 1667 at $l \sim 239.57$ and $b \sim -4.64$. These authors obtained an LSR radial velocity between $\sim 18.42$ and $\sim 23.62$ km s$^{-1}$ for the B cloud, and a kinematical distance between 1.7 and 2.1 kpc with errors of $\pm 0.5$ kpc from their CO observations. The kinematical distance largely differs from that determined using stars presumably being members of the region, which results in being between $\sim 300$ and $\sim 650$ pc (see MGA05).

From the data in GEDR3, we have obtained the distances, proper motions, and magnitudes of SPH 4 and SPH 4-South that are listed in Table 5. In addition, for comparison purposes, the same information has been obtained for Star 1 and Star 2 that are marked in Figures 2 and 3, and is included in Table 5.

The distance of SPH 4 is in agreement with the kinematical distance to cloud B, strongly suggesting that it is a member of LDN 1667. Star 1 and Star 2 present a similar distance and they should also be members of the cloud. Moreover, the proper motions of SPH 4, Star 1, and Star 2 present a similar magnitude and direction. We also note that the (LSR) radial velocity of SPH 4 ($\sim +15$ km s$^{-1}$) is similar to that of LDN 1667, although this could be a simple coincidence and
| Star   | Observed Wavelength (Å) | FWHM (Å) | \(W_\lambda\) (Å) | Line Identification | Figures |
|--------|------------------------|----------|------------------|-------------------|---------|
| SPH 4  | 4924.84                | 1.9      | 3.3              | Fe II (42)        | 10      |
| DG Cir | 4823.87                | 1.9      | 2.1              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 4994.65                | 1.3      | 0.8              | Fe II (36)        | 10      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5019.43                | 2.2      | 2.4              | Fe II (42)        | 11      |
| DG Cir | 5018.53                | 2.1      | 2.6              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5042.33                | 1.7      | 1.3              |                   | 11      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5050.60                | 0.8      | 0.4              |                   | 11      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5052.51                | 1.2      | 0.7              |                   | 11      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5080.42                | 1.7      | 1.2              |                   | 11      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5084.23                | 1.3      | 0.5              |                   | 11      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |
| SPH 4  | 5108.45                | 1.3      | 0.8              |                   | 12      |
| DG Cir | ...                    | ...      | ...              |                   |         |
| SPH 4- South | ... | ... | ... |               |         |
| R Mon | ...                     | ...      | ...              |                   |         |

Table 2 (Continued)
| Star   | Observed Wavelength ($\lambda$ Å) | FWHM ($\lambda$ Å) | $W_{\lambda}$ ($\lambda$ Å) | Line Identification | Figures  |
|--------|----------------------------------|--------------------|-----------------------------|---------------------|-----------|
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5217.17                          | ...                | ...                         | ...                 | broad double peak |
| DG Cir | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5227.95                          | 1.7                | 1.2                         | 13                  | ...       |
| DG Cir | 5226.72                          | 2.4                | 0.7                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5233.92                          | 0.9                | 0.3                         | 13                  | ...       |
| DG Cir | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5235.51                          | 2.0                | 1.6                         | Fe II(49) 5234.6    | ...       |
| DG Cir | 5234.48                          | 2.2                | 0.9                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5270.78                          | 1.9                | 2.1                         | 13                  | ...       |
| DG Cir | 5259.58                          | 2.0                | 1.2                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5276.95                          | 1.5                | 2.2                         | Fe II(49) 5276.0    | ...       |
| DG Cir | 5275.95                          | 2.0                | 1.5                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5283.89                          | ...                | ...                         | Fe II(41) 5284.1    | ...       |
| DG Cir | 5285.00                          | 1.1                | 1.2                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5317.58                          | ...                | ...                         | Fe II(49) 5316.2    | ...       |
| DG Cir | 5316.58                          | ...                | ...                         | ...                 | ...       |
| SPH 4- South | ...                              | ...                | ...                         | ...                 | ...       |
| R Mon  | ...                              | ...                | ...                         | ...                 | ...       |
| SPH 4  | 5363.80                          | 1.6                | 1.5                         | Fe II(48) 5362.9    | ...       |
| DG Cir | 5362.75                          | 1.7                | 0.8                         | ...                 | ...       |
| Star      | Observed Wavelength (Å) | FWHM (Å) | $W_\lambda$ (Å) | Line Identification | Figures |
|-----------|------------------------|----------|-----------------|---------------------|---------|
| SPH 4     | 5456.50                | 1.2      | 0.8             |                     | 15      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6138.27                | 2.1      | 1.6             |                     | 17      |
| DG Cir    | 6137.18                | 2.0      | 0.4             |                     |         |
| double peak |                     |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6149.68                |          |                 |                     | 17      |
| DG Cir    |                        |          |                 |                     |         |
| double peak |                     |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6401.19                | 1.7      | 0.4             |                     | 19      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6417.98                | 2.3      | 0.5             | Fe II(74)           | 19      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6416.71                |          |                 | asymmetric profile  |         |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6422.44                | 1.9      | 0.4             |                     | 19      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6432.40                | 1.9      | 0.4             | Fe II(40)           | 19      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6431.48                |          |                 | asymmetric profile  |         |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6456.23                | 2.1      | 0.9             |                     |         |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6457.53                | 1.8      | 1.3             | Fe II(74)           | 19      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 6516.4                 | 1.8      | 1.1             |                     |         |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 8348.97                | 5.8      | 1.3             |                     | 20      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 8389.13                | 1.6      | 2.2             |                     | 20      |
| DG Cir    |                        |          |                 |                     |         |
| SPH 4-     |                        |          |                 |                     |         |
| South     |                        |          |                 |                     |         |
| R Mon     |                        |          |                 |                     |         |
| SPH 4     | 8387.69                | 2.6      | 1.0             |                     |         |
the stellar velocity of SPH 4 should be used to make a better comparison.

The case of SPH 4-South is different. Its distance is clearly smaller than those of the other three stars and of LDN 1667. The magnitude of its proper motion is very different from those of the other three stars, although the direction coincides within the errors (Table 5). The radial velocity of SPH 4-South (∼−32 km s⁻¹) is very different from that of LDN 1667, although this value has been derived from the emission lines and should not necessarily represent that of the star. In general, the data seem to suggest that SPH 4-South is not related to SPH 4 and LDN 1667. However, we note that the errors in the distance and proper motion of SPH 4-South are considerably larger than those associated with the other three stars. In principle, the errors could be related to the

| Star           | Observed Wavelength (Å) | FWHM (Å) | Wλ (Å) | Line Identification | Figures |
|----------------|-------------------------|----------|--------|----------------------|---------|
| R Mon          | ...                     | ...      | ...    | ...                  | ...     |
| SPH 4          | 8394.65                 | 3.5      | 0.6    | H (P20)              | 8392.40 |
| DG Cir         | ...                     | ...      | ...    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |
| R Mon          | 8383.60                 | 9.5      | 1.8    | ...                  | ...     |
| SPH 4          | 8414.73                 | ...      | ...    | ...                  | ...     |

contaminated by OH emission

| Star           | Observed Wavelength (Å) | FWHM (Å) | Wλ (Å) | Line Identification | Figures |
|----------------|-------------------------|----------|--------|----------------------|---------|
| DG Cir         | 8412.93                 | 4.2      | 1.0    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |
| R Mon          | 8415.26                 | 10.9     | 2.3    | ...                  | ...     |
| SPH 4          | 8439.35                 | 5.4      | 1.0    | ...                  | ...     |
| DG Cir         | 8438.18                 | 4.4      | 1.1    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |
| R Mon          | 8440.38                 | 9.1      | 2.4    | ...                  | ...     |
| SPH 4          | 8448.01                 | 3.5      | 3.0    | O I 8446.74          | 20      |
| DG Cir         | 8446.43                 | 3.8      | 4.3    | ...                  | ...     |
| SPH 4-South    | 8446.19                 | 3.0      | 0.6    | ...                  | ...     |
| ...            | ...                     | ...      | ...    | ...                  | ...     |

... double peak

| Star           | Observed Wavelength (Å) | FWHM (Å) | Wλ (Å) | Line Identification | Figures |
|----------------|-------------------------|----------|--------|----------------------|---------|
| R Mon          | 8448.52                 | 5.3      | 4.5    | ...                  | ...     |
| SPH 4          | 8469.58                 | 2.9      | 1.0    | H (P17)              | 8467.80 |
| DG Cir         | 8467.22                 | 4.0      | 1.3    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |
| R Mon          | 8468.84                 | 7.9      | 2.0    | ...                  | ...     |
| SPH 4          | 8499.67                 | 3.9      | 27.4   | Ca II 8498.06        | 20      |
| DG Cir         | 8498.02                 | 3.6      | 30.0   | ...                  | ...     |
| SPH 4-South    | 8498.17                 | 5.5      | 5.4    | ...                  | ...     |
| R Mon          | 8499.98                 | 5.0      | 14.5   | ...                  | ...     |
| SPH 4          | 8515.64                 | 1.8      | 1.1    | Ca II 8498.06        | 20      |
| DG Cir         | ...                     | ...      | ...    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |
| R Mon          | 8544.31                 | 6.0      | 12.8   | ...                  | ...     |
| SPH 4          | 8599.73                 | 3.7      | 1.6    | H I 8598.39          | 21      |
| DG Cir         | 8598.28                 | 4.3      | 4.3    | ...                  | ...     |
| SPH 4-South    | ...                     | ...      | ...    | ...                  | ...     |

Note. Comments are provided for emission lines that present an asymmetric profile, a double peak, a flat-topped profile, or are contaminated by telluric lines. A few absorption lines were identified and are noticed.

...
brightness of the star, as can be inferred from Table 5 for Star 1, Star 2, and SPH 4. However, Star 1 and Star 2 are clearly fainter than SPH 4-South and show smaller errors in distance and proper motion than SPH 4-South. We suspect that the measurements of SPH 4-South might be affected by the presence of the nebula, which could introduce uncertainties in the measurements of its photocenter. Therefore, membership of SPH 4-South to LDN 1667 cannot be ruled out from the current data and obtaining its stellar velocity is mandatory to confirm or reject such a membership.

### Table 3

| Star      | J    | e     | H    | e     | K    | e     |
|-----------|------|-------|------|-------|------|-------|
| SPH 1     | 13.102| 0.027 | 11.961| 0.029 | 11.176| 0.023 |
| SPH 4     | 12.392| 0.028 | 11.517| 0.031 | 10.798| 0.029 |
| SPH 6     | 11.610| 0.024 | 10.351| 0.023 | 9.290 | 0.019 |
| SPH 17    | 12.802| 0.023 | 11.783| 0.037 | 10.523| 0.029 |
| SPH 21    | 12.884| 0.023 | 12.357| 0.021 | 12.202| 0.025 |
| SPH 22    | 13.181| 0.027 | 12.145| 0.022 | 11.245| 0.023 |
| SPH 24    | 12.608| 0.022 | 11.877| 0.021 | 11.381| 0.021 |
| SPH 4-South| 12.254| 0.056 | 11.094| 0.061 | 10.085| 0.030 |

We have presented high-resolution spectra of the emission-line star SPH 4 and of a new emission-line object, named SPH 4-South, that is presumably associated with a faint diffuse nebula detected in public images. We also analyzed narrowband and broadband images to investigate the faint nebula. By comparing the spectra of SPH 4 and SPH 4-South with similar ones of DG Cir and R Mon, respectively, we reclassify SPH 4 as a HAeBe star, correcting the previous T Tauri classification, and also suggest an HAeBe classification for SPH 4-South. An analysis of the $H-K$ versus $J-H$ color–color diagram by means of a $k$-NN algorithm provides support for the HAeBe classification of SPH 4-South. The two stars are detected in the four WISE bands and their W1–W2 and W2–W3 colors suggest a Class I and Class II classification for SPH 4 and SPH 4-South, respectively. The faint nebula appears associated with SPH 4-South. Both stars are observed toward the dark cloud LDN 1667. Using published data on LDN 1667 and GEDR 3 we conclude that SPH 4 is a member of the cloud. The GEDR 3 data of SPH 4-South seems to exclude its association with LDN 1667. Nevertheless, these data present relatively large errors that might be caused by the presence of the nebula, and membership of SPH 4-South to LDN 1667 still cannot be ruled out.

#### 7. Conclusions

![Figure 7. SPH 4, SPH 4-South, and stars classified as T Tauri stars by Pereira et al. (2001) (red stars) in the $H-K$ vs. $J-H$ diagram. Green crosses represent HAeBe stars with data taken from Vioque et al. (2018), and blue crosses represent T Tauri stars with data taken from Dahm & Simon (2005) and Percy et al. (2010).](image-url)
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**Table 4**

| Star            | W1  | e  | W2  | e  | W3  | e  | W4  | e  |
|-----------------|-----|----|-----|----|-----|----|-----|----|
| SPH 4           | 9.085 | 0.023 | 7.976 | 0.019 | 5.144 | 0.014 | 2.710 | 0.018 |
| SPH 4-South     | 8.746 | 0.025 | 7.845 | 0.021 | 5.827 | 0.019 | 4.033 | 0.039 |

**Table 5**

| Star    | Distance | Proper Motion | Magnitude | Proper Motion PA | G_Bp | G_CI | G_Rp |
|---------|----------|---------------|-----------|------------------|------|------|------|
| SPH 4   | 1387 ± 38 | 3.33 ± 0.02   | 321.5 ± 0.4 | 15.613 ± 0.010  | 14.675 ± 0.004 | 13.669 ± 0.007 |
| SPH 4-South | 896 ± 205 | 0.95 ± 0.27   | 309 ± 16   | 16.521 ± 0.029  | 15.740 ± 0.011 | 14.473 ± 0.025 |
| Star 1  | 1324 ± 145 | 3.43 ± 0.12   | 317.3 ± 2.2 | 19.473 ± 0.030  | 17.947 ± 0.003 | 16.556 ± 0.007 |
| Star 2  | 1381 ± 83  | 3.42 ± 0.06   | 321 ± 1    | 17.959 ± 0.036  | 16.608 ± 0.008 | 15.414 ± 0.026 |

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Figure 8. Same as Figure 7, but with a decision surface added. The surface (i.e., colored regions) was computed with the k-NN method (see the text). Note that SPH 4 falls close to the frontier between T Tauri and HAeBe stars and SPH4-South is on the HAeBe side. SPH 17 is the object with the highest H–K value among the sample of P2001.
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Appendix
Additional Figures

In this section we present additional figures (Figures 9–22) that compare the spectra of SPH 4 and SPH 4-South with those of DG Cir and R Mon, respectively.

![Figure 9. Normalized spectra of SPH 4, DG Cir, and SPH 4-South around the Hβ line.](image)
Figure 10. Normalized spectra of SPH 4 and DG Cir between 4900 and 5000 Å.
Figure 11. Normalized spectra of SPH 4 and DG Cir between 5000 and 5100 Å.
Figure 12. Normalized spectra of SPH 4 and DG Cir between 5100 and 5200 Å.
Figure 13. Normalized spectra of SPH 4 and DG Cir between 5200 and 5300 Å.
Figure 14. Normalized spectra of SPH 4 and DG Cir between 5300 and 5400 Å.
Figure 15. Normalized spectra of SPH 4 and DG Cir between 5400 and 5500 Å.
Figure 16. Normalized spectra of SPH 4, DG Cir SPH 4-South, and R Mon around the region of Na I lines. Notice the weak He I emission at 5876 Å, the photospheric broad Na I absorptions, and the circumstellar narrow Na I absorptions, as well as weak telluric emission Na I lines (including weak OH emission at $\sim$5888 Å) in the spectrum of SPH 4. In SPH 4-South we notice the circumstellar narrow Na I absorptions in the broad absorption profiles.
Figure 17. Normalized spectra of SPH 4, DG Cir, and R Mon between 6125 and 6275 Å.
Figure 18. Normalized spectra of SPH 4, DG Cir, SPH 4-South, and R Mon around the [O I] line at 6300 Å.
Figure 19. Normalized spectra of SPH 4 and DG Cir between 6360 and 6530 Å.
Figure 20. Normalized spectra of SPH 4, DG Cir, R Mon, and SPH 4-South between 8370 and 8525 Å. Narrow OH emission lines are seen in the spectra of SPH 4, DG Cir, and SPH 4-South.
Figure 21. Normalized spectra of SPH 4, DG Cir, R Mon, and SPH 4-South between 8525 and 8700 Å.
Figure 22. Normalized spectra of SPH 4, DG Cir, R Mon, and SPH 4-South between 8740 and 8840 Å. Narrow OH emission lines are seen in the spectra of SPH 4, DG Cir, and SPH 4-South.

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