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Identifying Ae/Be stars in *Gaia* low-resolution BP/RP spectra

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Abstract. Classical Be, and Herbig Ae/Be stars are mainly characterized by emission in the H*alpha* and H*beta* lines. These lines are essential to understanding the formation of massive stars and describing mass loss and stellar winds during stellar evolution. This study aims to characterize and detect classical Be and Herbig Ae/Be stars in *Gaia* BP/RP spectra, which allow us to investigate the complete stellar spectral range. Synthetic Δa and Hα index magnitude values were calculated from *Gaia* BP/RP spectra. Colour-colour diagrams were employed to distinguish emission-line objects from normal stars. With the proposed method here, we could unambiguously retrieve 90% of a sample of well-known emission-line objects. This shows that analyzing the 520 nm and Hα region efficiently discriminates emission-line objects from normal stars. No further assumptions about astrophysical parameters such as reddening, effective temperature, or IR excess are necessary.

Key words: Techniques: photometric – stars: emission-line, Be – stars: pre-main sequence

1. Introduction

Hot emission-line stars have been the focus of research for a long time. They are ideally suited for studying diverse astrophysical phenomena such as mass loss, circumstellar disks or shells, and pulsation. With the advent of large-scale spectroscopic surveys such as the Sloan Digital Sky Survey (SDSS; Blanton et al., 2017; Abdurro'uf et al., 2022) and the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST; Zhao et al., 2012; Cui et al., 2012) surveys, the research on these objects has seen a significant boost (e.g. Anusha et al., 2021; Shridharan et al., 2021; Zhang et al., 2022).

A diverse set of objects is lumped together under the heading of hot emission-line stars, such as the classical Be and B-type shell stars, young stellar objects like Herbig Ae/Be stars, B[e] stars, supergiants, mass transferring binaries or Wolf-Rayet stars (e.g. Rivinius et al., 2013).

Classically, Be stars are defined as stars that are not supergiants and show or have shown emission features in at least one Balmer line at least once (Collins, 1987). The observed emission features are mostly due to equatorial disks produced by stellar winds. Depending on the inclination one looks at the star, sometimes a narrow absorption feature is present in the emission line. This effect is less prominent when looking at the star's polar regions and gets stronger the closer one is to the equator (Slettebak, 1979; Rivinius et al., 2013). In addition, photometric variability on different timescales is commonly observed in these stars. Periodic variations on intermediate time scales (days to months) cannot be explained by non-radial pulsation, although the beating of closely spaced non-radial pulsation frequencies have been postulated as a possible explanation (Labadie-Bartz et al., 2017). Photometric variability on long time scales (months to decades) is generally attributed to (changes in) the circumstellar disc, most notably its development and dispersion. Discs are created through events referred to as outbursts, in which mass is elevated from the stellar surface and the development of, and mass transfer to, the disc is initiated. Outbursts are accompanied by characteristic photometric variations (e.g. Rivinius et al., 2003; Porter & Rivinius, 2003; Kurfürst et al., 2018). Emission phases may be replaced by shell and normal phases in the same object.

We here present our efforts at characterizing and finding hot emission-line stars in *Gaia* low-resolution BP/RP spectra (Carrasco et al., 2021; De Angeli et al., 2022) using a pre-selected sample of classical Be and Herbig Ae/Be stars as reference. This will help in the future detection of emission line stars even in spectra with (extremely) low spectral resolution such as the *Gaia* BP/RP spectra of *Gaia* DR3 and forthcoming data releases. Our method can be a new criterion for detecting such stars.

2. Target selection

We selected all Herbig Ae/Be and classical Be stars from the catalogues of Jaschek & Egret (1982), Bernhard et al. (2018), and Vioque et al. (2020) for which a BP/RP spectrum is available. Our sample consists of 794 objects with $3.2 < G < 12.7$ mag.

For the control sample of apparently normal stars, we chose all objects included in the paper by Paunzen & Prišegen (2022) and extended this sample with stars from Paunzen et al. (2005). This sample of stars has non-peculiar Δa values and can be used as a standard and reference.
Δa-photometry is a powerful tool in detecting magnetic chemically peculiar (mCP) stars (Paunzen et al., 2005). It uses the flux-depression at λ5200 (Kodaira, 1969) to do so. The method uses three narrowband filters: one to the left of the depression (g_1), one right on the depression (g_2), and one on the right of the depression (y). From the (synthetic) magnitudes in these filters, the peculiarity index a can be calculated:

$$a = g_2 - \frac{(g_1 + y)}{2}. \tag{1}$$

This quantity, however, is slightly colour/temperature dependent, and thus a Δa value is calculated as such:

$$\Delta a = a - a_0(g_1 - y). \tag{2}$$

All stars that lie more than 3σ above the "normality line" a_0 have a significant flux depression and can be taken as candidate peculiar stars.
We selected 435 stars of spectral types B0 to F7 with luminosity classes V to III. The astrophysical parameter space of stars beyond the zero-age main sequence should cover the entire pre-main sequence region (Haemmerlé et al., 2019). We note that both samples also include binary stars.

No cut according to the signal-to-noise ratios of the spectra was applied for both samples.

3. Methods and Results

To calculate the synthetic magnitudes, we first normalized all spectra to unity at a common wavelength of 402 nm. All spectra were brought to the same absolute flux at this wavelength region. No additional normalization was performed in the region of Hα. This technique was successfully applied to the synthetic Δa photometry (Sect. 3.1.) Applying a standard polynomial technique, the spectra were then interpolated to a one-pixel resolution of 0.1 nm in the wavelength regions from 480 to 580 nm and 610 to 700 nm. No further smoothing or cleaning algorithms were used. Each filter curve was folded with the corresponding spectrum as described in Stigler et al. (2014). The final magnitudes for all filters are in arbitrary units.

The calculated Δa and Hα index magnitude values for the sample of known Herbig Ae/Be and classical Be stars are presented in a text file provided as supporting material. The first ten rows are shown in Table 1 for guidance regarding the text file's form and content. *Gaia* data were gleaned from DR3 (Gaia Collaboration et al., 2016; Babusiaux et al., 2022; Gaia Collaboration et al., 2022).

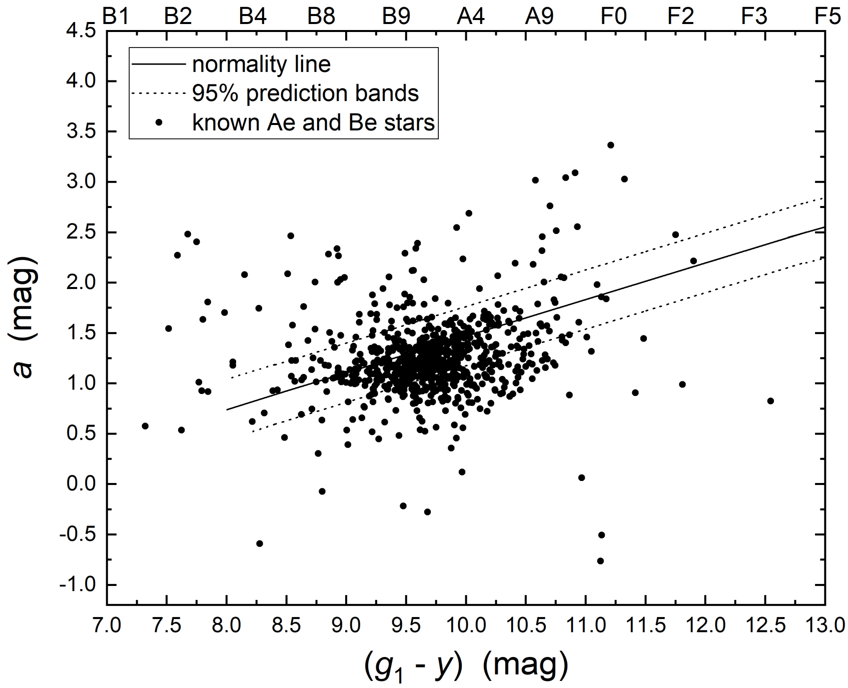

Figure 1. The sample of known Herbig Ae/Be and classical Be stars in the a versus $(g_1 - y)$ magnitude parameter space. As expected, most objects do not show any significant deviations from the normality line (solid line) and the 95% prediction bands for the standard stars (dotted lines; from Paunzen & Prišegen, 2022). Stars above the normality line are in the shell phase, and stars below are in the emission phase.

3.1. Δa photometry

Pavlovski & Maitzen (1989) analysed the different phases of classical Be stars within the Δa photometric system. They investigated, in particular, the case of Pleione, which is quite outstanding. It reached a Δa value of +36 mmag in the shell phase and dropped quite rapidly to zero within a year. Detailed measurements for 59 objects were presented by Paunzen et al. (2005) with extreme values for the emission phase of −19 mmag. The negative Δa values found are caused by emission in iron and magnesium lines (Hanuschik et al., 1996).

We used the three filters defined in Paunzen & Prišegen (2022) with a bandwidth of 13 nm and central wavelengths of g_1 (501 nm), g_2 (521.5 nm), and y (548.5 nm).

In Fig. 1, the results for the sample of known Herbig Ae/Be and classical Be stars are shown, together with the normality line and its 95% prediction bands.

Several extreme outliers were omitted from the plot. The objects show the same behaviour as the ones published by Paunzen et al. (2005, see Fig. 5 therein), who employed classical photoelectric Δa photometry. From the 794 objects, 95 (12%) are above and 194 (24%) below the corresponding 95% prediction bands. Thus, almost two-thirds of the classical Be and Herbig Ae/Be stars cannot be detected at the 520 nm region. Nevertheless, a significant negative or positive Δa value can help to corroborate the results from the Hα region.

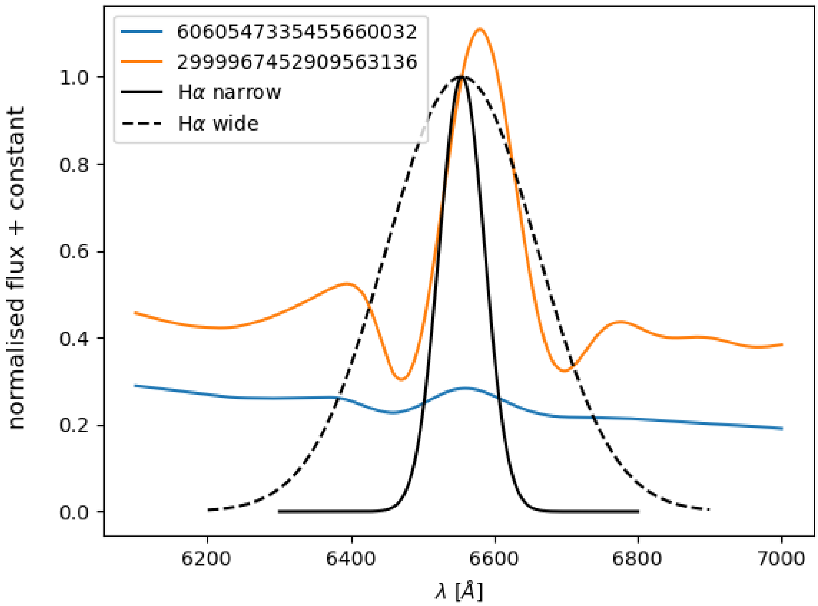

Figure 2. Filter curves used to probe the Hα line. Also shown are two example spectra which were offset by a constant value. The lower blue spectrum belongs to a star with some Hα emission (*Gaia* DR3 6060547335455660032). The upper orange spectrum shows a very strong emission feature (*Gaia* DR3 2999967452909563136).

3.2. Hα photometry

One of the main characteristics of classical Be and Herbig Ae/Be stars is the variability of the hydrogen lines, which manifests itself especially in the Hα and Hβ lines. On very different time scales, these lines are observed in strong emission or absorption as in normal stars. Another essential aspect is the vari-

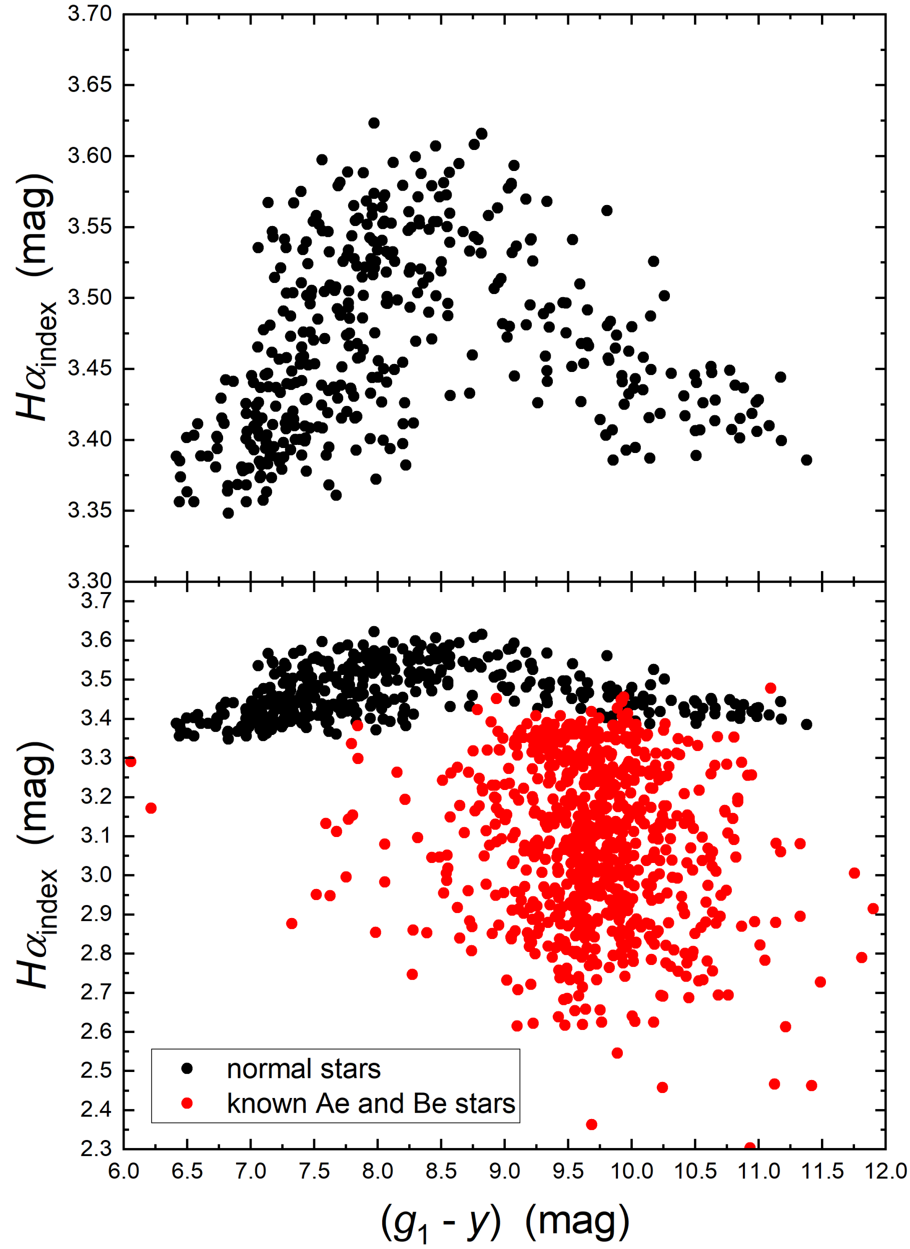

Figure 3. The samples of normal stars (filled black circles) and known Herbig Ae/Be and classical Be stars (filled red circles) in the Hα index versus $(g_1 - y)$ magnitude parameter space. Any object with Hα index $<$ 3.35 over the full colour (effective temperature) range is assumed to show emission in the Hα line.

Table 1. Elementary data for the sample of known Herbig Ae/Be and classical Be stars. The columns denote: (1) *Gaia* DR3 identifier. (2) 2MASS identifier (Skrutskie et al., 2006). (3) Right ascension (J2000; *Gaia* DR3). (4) Declination (J2000; *Gaia* DR3) (5) *G*-band mean magnitude (*Gaia* DR3). (6) Calculated $(g1 - y)$ colour index. (7) Calculated Δa value. (8) Calculated Hα value.

(1) Gaia_ID	(2) 2MASS_ID	(3) α(J2000)	(4) δ(J2000)	(5) G mag	(6) $(g1 - y)$	(7) Δa	(8) Hα
1384384649468452224	15553059+4233582	238.877325	42.566264	5.6984	9.504	−0.003	3.386
1741560280196688000	21352379+0929184	323.849126	9.488430	10.0942	9.388	+0.077	3.132
1808447386454770304	20170976+1552215	304.290707	15.872623	7.5656	10.151	+0.143	3.174
1817679706409974400	20383016+2119439	309.625721	21.328888	9.2816	8.935	+0.069	3.172
1824520940823718656	19465768+1814559	296.740351	18.248855	10.4601	9.489	+0.602	3.379
1826951544369716480	20024644+2151160	300.693478	21.854407	8.2510	9.980	−0.403	2.928
183709705601742592	05254477+3538499	81.436597	35.647184	8.1591	7.624	−0.071	2.949
184497471323752064	05223522+3740336	80.646805	37.675993	7.2317	10.032	−0.459	2.827
1849597571190605952	21354448+2944439	323.935321	29.745477	8.0383	9.422	−0.265	2.639
185767888290202880	05095643+3700158	77.485137	37.004430	8.2110	9.952	−0.171	3.129

ability of the line-profiles, which may show different shapes within a few hours or remain stable over a timescale of years (Catanzaro, 2013).

To identify emission-line objects, we chose an approach similar to the calculation of the Hβ index in the Strömgren-Crawford system (Strömgren, 1966). The idea is to measure the flux of the entire Hα line and compare this to the flux in the line core. The ratio (Hα index) consequently measures any deviations, particularly emission, in the core. For detection efficiency, the shift of an emission feature relative to the central wavelength plays a significant role. Therefore, to come up with an optimum solution, we tried several configurations and finally settled upon a solution with filters (represented as a Gaussian function) centered on 655.5 nm with full width at half maxima of 12.5 and 3.5 nm, respectively. The filter curves and two example spectra are shown in Fig. 2, which also illustrates a classical P Cygni profile with the corresponding radial velocity shifts.

The final diagnostic diagram was constructed using $(g_1 - y)$ magnitudes and is shown in Figure 3, which presents the results for the sample of normal stars and the sample of classical Be and Herbig Ae/Be stars. In general, we assume that any object with Hα index < 3.35 over the full colour (effective temperature) range shows emission in the Hα line. This is a quite strict criterion that selects 711 (90%) of the 794 sample objects.

4. Conclusions

Our results show that synthetic photometry of the 520 nm and Hα region is an efficient tool for finding hot emission-line objects and that *Gaia* BP/RP spectra are excellently suited for this purpose. The well-established tool of Δa photometry covered the bluer spectral range, for which photoelectric measurements are also available. To probe the Hα region, we employed a wide and a narrow filter and calculated the ratio of the fluxes in both filters.

We analyzed the behavior of a sample of classical Be and Herbig Ae/Be stars and a control sample of normal stars in the corresponding colour-colour diagrams. About 90% of the emission-type objects could be unambiguously retrieved in this way. The method employed here can, therefore, be used as a blueprint in future studies to efficiently search for emission-line objects in *Gaia* BP/RP spectra.

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References

Abdurro'uf, Accetta, K., Aerts, C., et al., The Seventeenth Data Release of the Sloan Digital Sky Surveys: Complete Release of MaNGA, MaStar, and APOGEE-2 Data. 2022, *Astrophysical Journal, Supplement*, **259**, 35, DOI: 10.3847/1538-4365/ac4414

Anusha, R., Mathew, B., Shridharan, B., et al., Identification of new classical Ae stars in the Galaxy using LAMOST DR5. 2021, *Monthly Notices of the RAS*, **501**, 5927, DOI: 10.1093/mnras/staa3964

Babusiaux, C., Fabricius, C., Khanna, S., et al., Gaia Data Release 3: Catalogue Validation. 2022, *arXiv e-prints*, arXiv:2206.05989

Bernhard, K., Otero, S., Hümmerich, S., et al., An investigation of the photometric variability of confirmed and candidate Galactic Be stars using ASAS-3 data. 2018, *Monthly Notices of the RAS*, **479**, 2909, DOI: 10.1093/mnras/sty1320

Blanton, M. R., Bershady, M. A., Abolfathi, B., et al., Sloan Digital Sky Survey IV: Mapping the Milky Way, Nearby Galaxies, and the Distant Universe. 2017, *Astronomical Journal*, **154**, 28, DOI: 10.3847/1538-3881/aa7567

Carrasco, J. M., Weiler, M., Jordi, C., et al., Internal calibration of Gaia BP/RP low-resolution spectra. 2021, *Astronomy and Astrophysics*, **652**, A86, DOI: 10.1051/0004-6361/202141249

Catanzaro, G., Spectroscopic atlas of Hα and Hβ in a sample of northern Be stars. 2013, *Astronomy and Astrophysics*, **550**, A79, DOI: 10.1051/0004-6361/201220357

Collins, George W., I., The Use of Terms and Definitions in the Study of be Stars (review Paper). 1987, in *IAU Colloq. 92: Physics of Be Stars*, ed. A. Slettebak & T. P. Snow, 3

Cui, X.-Q., Zhao, Y.-H., Chu, Y.-Q., et al., The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST). 2012, *Research in Astronomy and Astrophysics*, **12**, 1197

De Angeli, F., Weiler, M., Montegriffo, P., et al., Gaia Data Release 3: Processing and validation of BP/RP low-resolution spectral data. 2022, *arXiv e-prints*, arXiv:2206.06143, DOI: 10.48550/arXiv.2206.06143

Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al., The Gaia mission. 2016, *Astronomy and Astrophysics*, **595**, A1, DOI: 10.1051/0004-6361/201629272

Gaia Collaboration, Vallenari, A., Brown, A. G. A., et al., Gaia Data Release 3: Summary of the content and survey properties. 2022, *arXiv e-prints*, arXiv:2208.00211

Haemmerlé, L., Eggenberger, P., Ekström, S., et al., Stellar models and isochrones from low-mass to massive stars including pre-main sequence phase with accretion. 2019, *Astronomy and Astrophysics*, **624**, A137, DOI: 10.1051/0004-6361/201935051

Hanuschik, R. W., Hummel, W., Sutorius, E., Dietle, O., & Thimm, G., Atlas of high-resolution emission and shell lines in Be stars. Line profiles and short-term variability. 1996, *Astronomy and Astrophysics, Supplement*, **116**, 309

Jaschek, M. & Egret, D., Catalog of Be stars. in , *Be Stars*, ed. M. Jaschek & H. G. Groth, Vol. **98**, 261

Kodaira, K., Osawa's Peculiar Star HD 221568. 1969, *Astrophysical Journal, Letters*, **157**, L59, DOI: 10.1086/180385

Kurfürst, P., Feldmeier, A., & Krtička, J., Two-dimensional modeling of density and thermal structure of dense circumstellar outflowing disks. 2018, *Astronomy and Astrophysics*, **613**, A75, DOI: 10.1051/0004-6361/201731300

Labadie-Bartz, J., Pepper, J., McSwain, M. V., et al., Photometric Variability of the Be Star Population. 2017, *Astronomical Journal*, **153**, 252, DOI: 10.3847/1538-3881/aa6396

Paunzen, E. & Prišegen, M., The detection of magnetic chemically peculiar stars using Gaia BP/RP spectra. 2022, *Astronomy and Astrophysics*, **667**, L10, DOI: 10.1051/0004-6361/202244839

Paunzen, E., Stütz, C., & Maitzen, H. M., On the detection of chemically peculiar stars using Δa photometry. 2005, *Astronomy and Astrophysics*, **441**, 631, DOI: 10.1051/0004-6361:20053001

Pavlovski, K. & Maitzen, H. M., Delta-a-photometry of Be shell stars. 1989, *Astronomy and Astrophysics, Supplement*, **77**, 351

Porter, J. M. & Rivinius, T., Classical Be Stars. 2003, *Publications of the ASP*, **115**, 1153, DOI: 10.1086/378307

Rivinius, T., Baade, D., & Štefl, S., Non-radially pulsating Be stars. 2003, *Astronomy and Astrophysics*, **411**, 229, DOI: 10.1051/0004-6361:20031285

Rivinius, T., Carciofi, A. C., & Martayan, C., Classical Be stars. Rapidly rotating B stars with viscous Keplerian decretion disks. 2013, *Astronomy and Astrophysics Reviews*, **21**, 69, DOI: 10.1007/s00159-013-0069-0

Shridharan, B., Mathew, B., Nidhi, S., et al., Discovery of 2716 hot emission-line stars from LAMOST DR5. 2021, *Research in Astronomy and Astrophysics*, **21**, 288, DOI: 10.1088/1674-4527/21/11/288

Skrutskie, M. F., Cutri, R. M., Stiening, R., et al., The Two Micron All Sky Survey (2MASS). 2006, *Astronomical Journal*, **131**, 1163, DOI: 10.1086/498708

Slettebak, A., The Be Stars. 1979, *Space Science Reviews*, **23**, 541, DOI: 10.1007/BF00212356

Stigler, C., Maitzen, H. M., Paunzen, E., & Netopil, M., Spectrophotometric analysis of the 5200 Å region for peculiar and normal stars. 2014, *Astronomy and Astrophysics*, **562**, A65, DOI: 10.1051/0004-6361/201322300

Strömgren, B., Spectral Classification Through Photoelectric Narrow-Band Photometry. 1966, *Annual Review of Astron and Astrophys*, **4**, 433, DOI: 10.1146/annurev.aa.04.090166.002245

Vioque, M., Oudmaijer, R. D., Schreiner, M., et al., Catalogue of new Herbig Ae/Be and classical Be stars. A machine learning approach to Gaia DR2. 2020, *Astronomy and Astrophysics*, **638**, A21, DOI: 10.1051/0004-6361/202037731

Zhang, Y.-J., Hou, W., Luo, A. L., et al., A Catalog of Early-type Hα Emission-line Stars and 62 Newly Confirmed Herbig Ae/Be Stars from LAMOST Data Release 7. 2022, *Astrophysical Journal, Supplement*, **259**, 38, DOI: 10.3847/1538-4365/ac4964

Zhao, G., Zhao, Y.-H., Chu, Y.-Q., Jing, Y.-P., & Deng, L.-C., LAMOST spectral survey — An overview. 2012, *Research in Astronomy and Astrophysics*, **12**, 723