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Identification of a rare class of emission-line stars in transition between pre-main sequence to Main Sequence phase

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Abstract

Over time, pre-main-sequence (PMS) stars evolve into main-sequence (MS) stars. Stars evolving from PMS to MS phase is a significant subject of research that aims to better understand stellar phases and their properties. Existing literature shows a lack of study of stars in between PMS and MS phase. 'We focused on what belongs in the midst of these two phases. Classical Be (CBe) and Herbig Ae/Be (HAeBe) stars, corresponding to MS and PMS phases, are two well known categories of emission-line stars. Through optical and infrared photometric analysis of a sample of 2167 CBe and 225 HAeBe stars, we identified 98 such rare stars which are in transition between PMS and MS phase. Those rare stars are termed as 'Transition Phase' (TP) candidates in our study. Using the machine learning approach, the potential of the identified TP candidates was verified. 'This article

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provides a brief overview of the research contributions made by the CHRIST (Deemed to be University) team in this field.

Keywords: Emission-line stars, Be star, Herbig Ae/Be star, Transition Phase candidates

1. Introduction

A clear night sky gives an ever - changing array of wonderful sights to see – Moon, planets, stars, even a good number of star clusters and nebulae. Observing the night sky and studies of it has a historical place in both ancient and modern cultures. Modern science and present day technology have certainly provided us the opportunity to view the universe in much depth, thus revealing the deep insights of different cosmic objects, which otherwise remained hidden from human eyes for centuries. We now have a pretty good understanding about the stars, their properties and evolution.

It is known that star formation of massive stars proceed through well studied, definitive stages such as protostar and pre-main sequence phase, before reaching the main sequence. A protostar is a very young star that is still gathering mass from its parent molecular cloud. The protostellar phase is the earliest one in the process of stellar evolution. For a low-mass star (i.e. that of the Sun or lower), it lasts about 500,000 years. In brief, this stage can be considered as the infancy period of a star. Next, Pre-main sequence (PMS) stars are those which are gradually attaining youth. Hydrogen fusion has not yet started in their cores, but the temperature is gradually rising. Loosely, we can say that this is a star's child or adolescent stage. When such PMS stars graduates to youth, we call them Main sequence (MS) stars. This is certainly the youth stage of stars where hydrogen is fusing to helium in their cores, like our Sun.

The above discussion conveys that every PMS star evolves into MS stage over a period of time. Tracking the transition phase between PMS and MS stars can provide a wealth of information about stellar evolution. Our recent study at CHRIST (Deemed to be University) has identified a sample of rare stars which are probably undergoing a transition from PMS Herbig Ae/Be to MS classical Be phase, making ours the first study ever to identify such rare class of transition phase stars (Bhattacharyya et al. 2021). Both these two types, Herbig Ae/Be and classical Be, belong to the category of emission-line stars. So an understanding of emission-line stars and also both these two types of stars are necessary to grasp the essence of the present article. The following subsection discusses what are emission-line stars and henceforth provide a brief idea about these two categories of stars.

2. Emission-line stars

Stars usually show absorption lines in their optical spectra. However, there exist stars which also exhibit emission lines of different elements. Broadly known as 'emission-line stars', they are widely distributed on the Hertzsprung-Russel (HR) diagram. They are further classified based on their spectral type and/or evolutionary phase or due to the association with a binary companion. The different classes of emission-line stars along with their subclasses are detailed below:

i) Pre-main sequence stars - T Tauri stars, Herbig Ae/Be stars.

ii) Early-type stars - Luminous blue variables (LBV), Of/ Oe/ Be/ Ae stars, Wolf Rayet (WR) stars.

iii) Late-type stars - Flare stars, Mira variables, red giants, dMe stars.

iv) Close binaries: symbiotic stars, cataclysmic variables (CV), Algol type stars.

Extensive studies have revealed that these emission lines originate primarily through three different ways: i) presence of some circumstellar envelope or outer stellar atmospheres, ii) due to some stellar activities such as flare outbursts or appearance of bright star spots, and iii) mass exchange in binary systems. Studies of emission-line stars provide tools for understanding the dynamic structure and physical state of circumstellar discs and stellar active regions. Exploring the fine structure of emission phenomenon has become possible through sophisticated ground-based observations combined with space based studies. This has also helped in developing reliable models of stellar activities.

Fig. 1 shows a schematic diagram to demonstrate the locations of different types of emission-line stars on the HR diagram. It is visible from the diagram that emission-line stars are mostly concentrated in the region belonging to early and late-type stars.

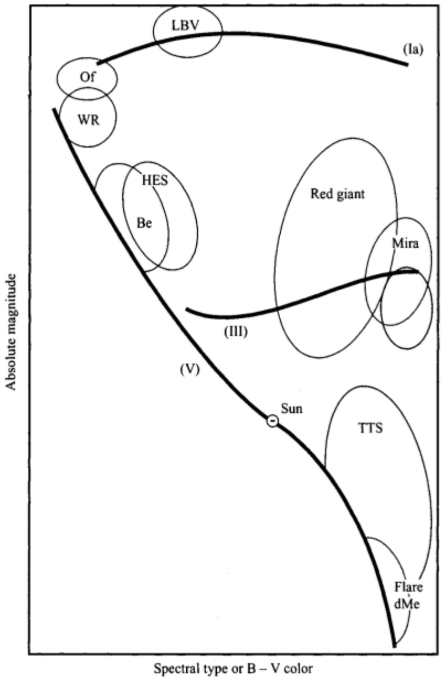

Figure 1: Distribution of different types of emission-line stars in the HR diagram. Figure is taken from Kogure & Leung (2007).

2.1. Classical Be stars

In the category of emission-line stars, a Classical Be (CBe hereafter) star holds a special class. They are B-type, massive stars in MS stage surrounded by a geometrically thin, equatorial, gaseous decretion disc that revolves around the central star in near Keplarian rotation (Meilland et al. 2007). The existence of such a circumstellar, gaseous disc was first suggested by Struve (1931). Collins (1987) defined a CBe star as: "a non-supergiant B star whose spectrum has, or had at some time, one or more Balmer lines in emission". They belong to luminosity class III - V. But this definition is incomplete since it cannot differentiate CBe stars from other kind of B-type stars where emission lines are produced from different physical mechanisms. Moreover, rapid rotation, another major feature of CBe stars, is not considered in this definition.

In the Milky Way, around 15-20% among all B-type stars are estimated to be CBe stars. Their mass and radii range within $M_{\star}\sim3.6 - 20\ M_{\odot}$, and $R_{\star}\sim2.7 - 15\ R_{\odot}$ (Cox 2000), respectively. Studies of several authors (Slettebak 1982; Mermilliod 1982; Mathew et al. 2012; Arcos et al. 2017; Banerjee et al. 2021) have shown that the peak incidence of CBe stars generally occur at B2 spectral type. The reason behind such a peak occurrence at B2 type is still an open issue. Fig. 2 shows a schematic representation of a CBe star. A review of CBe star studies till date can be found in Rivinius et al. (2013) and Porter & Rivinius (2003). Moreover, Banerjee et al. (2020) provides a wonderful description about the importance of studying CBe stars and their different observable properties.

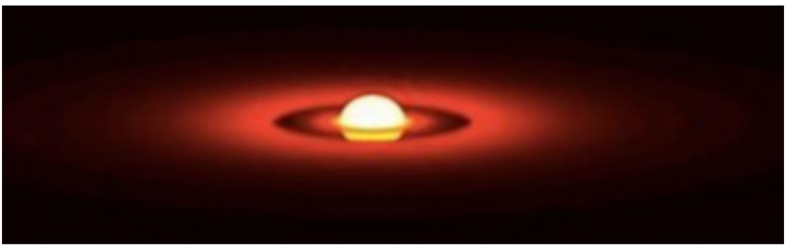

Figure 2: A schematic representation of a CBe star (credit: Sigut, A; Western University, Canada)

2.2. Herbig Ae/Be stars

A Herbig Ae/Be (HAeBe hereafter) star is an intermediate mass PMS star (2 – 8 $M_{\odot}$) possessing a gaseous disc, which is surrounded by a dusty outer envelope (Waters & Waelkens 1998). HAeBe stars were classified as a distinct group of objects by Herbig (1960). The PMS nature of HAeBe stars was confirmed by Strom et al.(1972) indicating that their ages are within the range of 0.1-1 Myr. They also show emission-lines of various species in their spectra (similar to that of CBe stars) and exhibit infrared (IR) excess

(Davies et al. 1990; van den Ancker et al. 1997) in the continuum, suggestive of hot and/or cool dust in the circumstellar medium (CSM; Hillenbrand et al. 1992a, Malfait et al. 1998). The currently accepted definition of HAeBe stars was proposed by The et al. (1994), Waters & Waelkens (1998) and Vieira et al. (2003) which incorporates the following two criteria: (a) Pre-main sequence stars with spectral types A–F that exhibit emission lines in their spectra and (b) that exhibit a considerable infrared (IR) excess due to a hot or cool circumstellar dust shell, or a combination of both the criteria. Fig. 3 obtained using the Ks band, outlining the polarised light emission, which is indicative of a disk structure associated with the star.

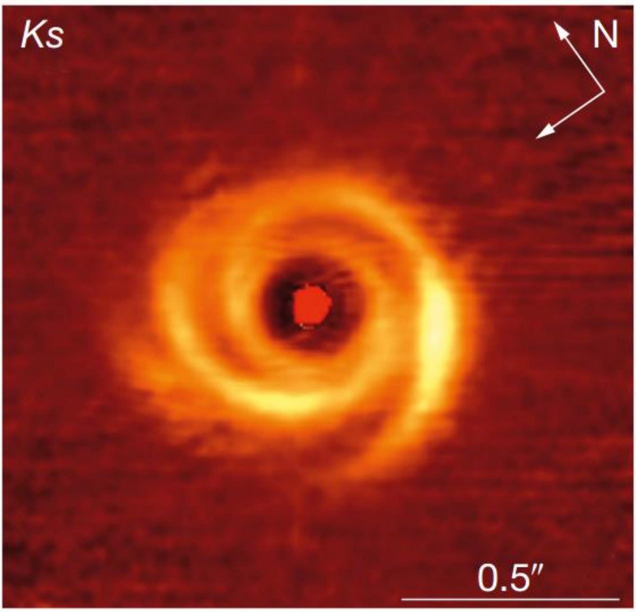

Figure 3: An image of the Herbig Be star HD 135344B which is taken using the Ks band (polarised light emission). Image adopted from Garufi et al. (2013)

In the Milky Way, it has been observed that less than 4% of the A and B-type PMS stars are actually HAeBe stars (Bohm & Balona 2000). The HAeBe phenomenon provides unique insights into the PMS phase of young stars. At this stage, they are dominated by gravitational contraction. Since these stars are deeply immersed in circumstellar gas and dust, and their spectra exhibit emission lines, it is difficult to determine stellar parameters such as luminosity, effective temperature and surface gravity (Folsom et al. 2012).

3. Stars in transition between PMS to MS phase

Spectra of both CBe (e.g. Banerjee et al. 2021; Mathew & Subramaniam 2011; Hanuschik 1996; Slettebak 1982) and HAeBe stars (e.g. Alecian et al. 2012; Hern □andez et al. 2004; Boehm & Catala 1994; Hamann & Persson 1992) show emission lines of different elements such as hydrogen, iron, oxygen, helium and calcium. Fig. 4 presents a representative spectra of a CBe star HD 55606 showing different spectral features in the whole optical wavelength range of 3800 – 9000 Å.

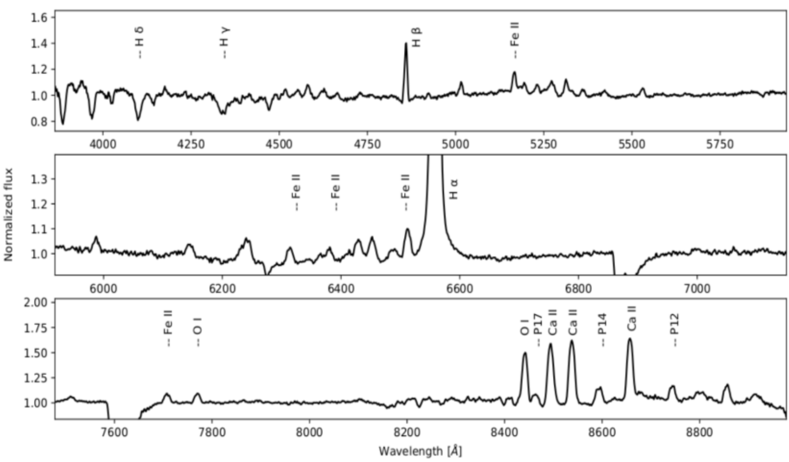

Figure 4: Representative spectra of a CBe star HD 55606 showing different spectral features in the wavelength range of 3800 - 9000 ˚A. Figure adopted from Banerjee et al. (2021).

HAeBe stars exhibit both permitted and forbidden emission lines. These lines provide necessary information both about the regions of their formation, and also the structure and composition of the region. However, most of the HAeBe stars show only permitted emission lines in their spectra and hence it is difficult to distinguish an HAeBe star from a CBe star. It may be noted that a few HAeBe stars show forbidden emission lines of [OI] 6300, 6363 Å in their spectra. Hence, if forbidden lines are present in the spectrum, it can be used as a criterion to separate HAeBe and CBe stars since CBe stars do not show forbidden emission lines in the spectra. However, one can distinguish them in terms of IR excess which denotes the excess flux over the continuum in the IR regime. CBe stars show comparatively lower IR excess than HAeBe stars due to the absence of dust in their disc.

Now, the pertinent question is, `Can IR excess be used to identify Ae/Be stars in transition from PMS to MS'? Interestingly, analysis of the near-IR color-color diagrams of emission-line stars reveal the existence of stars that lie between the location of HAeBe and CBe stars (Mathew et al. 2008). They are likely to exhibit properties of both these classes. The star 51 Oph is a probable example of this class (Jamialahmadi et al. 2015).

Dunkin et al. (1997a) derived the rotational velocity (vsini) for 51 Oph to be = 267 ±5 km/s, which is quite high than the expected vsini for HAeBe stars. In another subsequent work, Dunkin et al. (1997b) observed double-peak Hα emission in 51 Oph, indicating the presence of a circumstellar disc; similar to what was noticed by Jamialahmadi et al. (2015). Later, Malfaitet al. (1998) and Leinert et al. (2004) found that the dusty disc of this star is much smaller (< 2 au) than that of other HAeBe stars. By analyzing ISO spectra, Van den Ancker et al. (2001) and Meeus et al. (2001) confirmed that 51 Oph possesses more amount of gas than other HAeBe stars. According to Jamialahmadi et al. (2015), 'this star appears to be a peculiar source in an unusual transitionalstate'. Subsequently, Jamialahmadi et al. (2018) concluded that 51 Oph behaves similar to a CBe and also a HAeBe star. From these studies, 51 Oph has emerged as the leading contender for being a transition phase star. Motivated by these studies we set out to identify more stars similar to 51 Oph and the present work explains the initial efforts in this direction.

4. Defining 'Transition Phase' candidates

It is important to note that there exists another form of well-known object in the literature called 'transitional disc' candidates (TD candidates hereafter). They differ from the candidates we have proposed here not only in terms of spectral type, but also in terms of evolutionary phase. TD candidates are primarily a subset of T Tauri stars that provide insight into how gas and dust discs grow into planetary systems (Espaillat et al. 2014). Such TD candidates possess a small excess in the near - and mid-IR regions and a considerable excess in the far-IR regime (Strom et al. 1989; Skrutskie et al. 1990). This suggests the presence of an inner cavity in the disc structure of these stars.

The above discussion emphasizes the need to also distinguish TD candidates from the before mentioned transition phase stars. Hence, in Bhattacharyya et al. (2021) we introduced the term 'Transition Phase' candidates to denote those stars evolving from PMS to MS phase. Hereafter, designated as 'TP candidates', these stars will be considered as those which are located in a region between HAeBe and CBe stars.

5. Pertinent questions regarding TP candidates

Finkenzellar & Mundt (1984) identified two distinct regions for HAeBe and CBe stars based on the analysis of near-IR color-color diagram. Now, the natural questions which come to mind are: 'Can any star lie in some location between these two regions?', 'if so, how we should define them?' and 'is there any connection between these two classes?' Mathew et al. (2008) studied 207 open clusters younger than 100 Myr and identified 152 CBe stars in 42 clusters. Interestingly, they also detected a few more stars which are situated in a region somewhere in between HAeBe and CBe stars in the near-IR color-color diagram. Fig. 5 presents the result which was observed by Mathew et al. (2008).

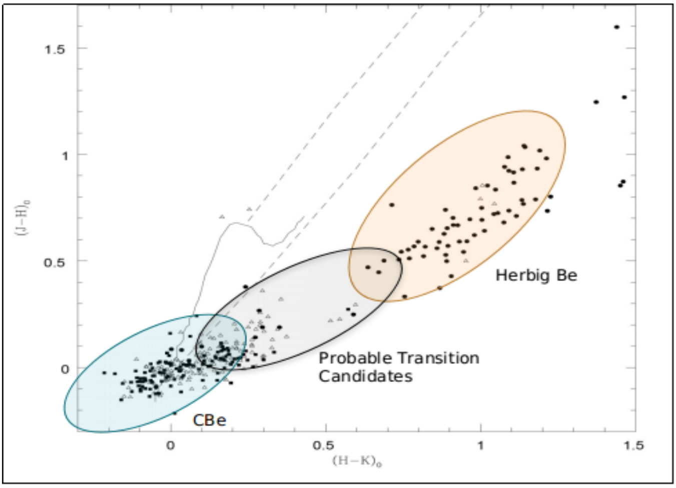

Figure 5: Extinction-corrected NIR color-color diagram of 157 identified emission-line stars (open triangles) as found by Mathew et al. (2008) in 42 open clusters with MS represented by the bold curve and reddening vectors indicated by dashed lines (Koornneef 1983). The known CBe stars (filled squares) and HBe stars (filled circles) from the catalogues of Jaschek & Egret(1982) and The et al. (1994), respectively, are also shown in the figure. It is seen that a few stars are located in a region somewhere in between HBe and CBe stars. For representation purpose, the region containing the most concentration of CBe and HBe stars are marked with blue and red ellipses, respectively. The candidates which appear to fall in between these two regions is marked with a grey ellipse. This grey region certainly constitutes of those stars which we termed as 'Transition Phase' candidates.

Such an intriguing observation raised a few obvious questions, 'what type of candidates are these?', 'do they belong to a different class of stars?' or 'are they in some sort of transition between the HAeBe and CBe phase?'. Later, Martayan et al. (2011) asked a similar kind of question as well: "What kinds of objects are responsible for the formation of Be stars and their rapid rotation? Are they connected to the Herbig Ae/Be objects?"

Looking through the literature, we found the unusual star 51 Oph, which has already raised the possibility of being a candidate with properties of both HAeBe and CBe stars. So the obvious questions are: 'is 51 Oph in a transition phase from HAeBe to CBe star?', or 'is this star a TP candidate?', and 'how can we detect additional such TP candidates?', 'what are their properties?' and so on.

6. Research on 'TP candidates' at the CHRIST (Deemed to be University)

The above discussed questions served as the motivation for us to start our ambitious research project. Literature review showed that no study has been performed till date to identify stars which might be in transition between HAeBe and CBe phase. This inspired us, a team of 6 researchers from the Department of Physics and Electronics, to look for more such stars, which we define through this work as 'TP candidates': stars evolving from PMS to MS phase.

CHRIST (Deemed to be University) hosts an active research group (the largest in the country) dedicated in studying various aspects of emission-line stars during the last seven years. Utilizing the experience they possess, we performed photometric analysis of a sample of 2167 CBe and 225 HAeBe stars obtained from the literature. Through developing a novel technique and thorough analysis, we were able to identify a sample of 98 stars evolving from PMS to MS phase. The result of our study is discussed in detail in Bhattacharyya et al. (2021). Interestingly, the detected 98 TP candidates are indeed found to possess rotational velocity in between CBe and HAeBe stars, which is reconfirmed by machine learning approach.

We estimated the age and mass of 58 among the 98 TP candidates to beranging within 0.1-5 million years (Myr) and 2-10.5 M$\odot$ (meaning 2 - 10.5 times that of solar mass), respectively. As per the near-infrared color—color diagram analysis, the TP candidates are located in the area between $0.12 < H - Ks < 0.41$, which is shared by the CBe and HAeBe regions (see Fig. 6). However, the detail properties of these newly identified stars are still unknown. Moreover, we verified the nature of the identified TP candidates using the WISE color-color diagram, rotational velocity (vsini) distribution study and over sampling approach from machine learning technique. We found that majority of the identified TP candidates are lying within the range of $0.2 < W1 - W2 < 0.5$ and $0.6 < W2 - W3 < 1.1$, which is well within the overlapping region of CBe and HAeBe stars. This result suggests that the mid-IR excess observed in the case of TP candidates is similar to that of CBe and HAeBe stars. However, through vsini study we found that for

HAeBe stars vsini ranges within 50–125 kms/s, whereas in case of CBe stars vsini ranges within 175–300 kms/s, respectively. For TP candidates vsini exhibit bimodal distribution with peaks at 175–225 kms/s and 275–300 kms/s, respectively (Bhattacharyya et al. 2021). This result implies that vsini for the TP candidates are greater than the HAeBe stars and lesser or equal to the upper range of CBe star. Our oversampling study using machinelearning approach also provided satisfactory results.

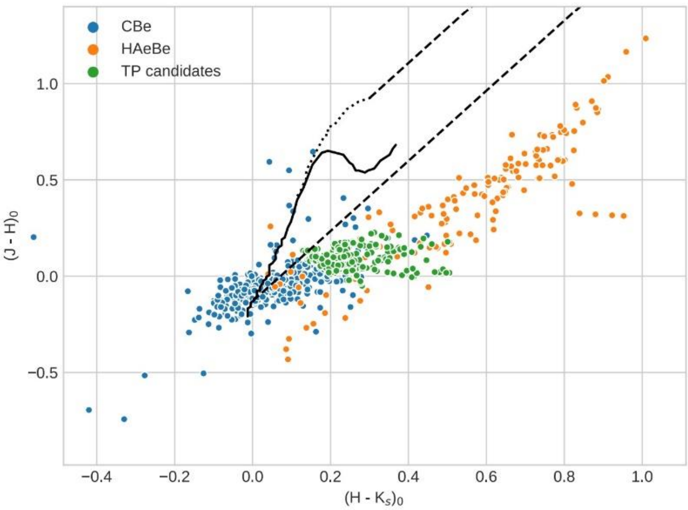

Figure 6: The near-IR color-color diagram of 352 CBe and synthetically oversampled 176HAeBe and TP candidates obtained using the new oversampled dataset (Bhattacharyya et al.2021). It is clearly evident from the plot that the TP candidates are well positioned between the distribution of CBe and HAeBe stars. It is observed that most of the TP candidates are falling in the region between 0.12 <H-Ks <0.41. The main-sequence, giant branch, and thereddening vectors are represented by solid, dotted, and dashed lines, respectively, as adopted from Koornneef (1983).

Furthermore, we performed a comparative study of the identified TP candidates with previously detected TD candidates for understanding whether the newly identified sample are different in properties than those of the known category of TD candidates or not (Bhattacharyya 2021, MPhil thesis). Our results suggest that the TDCs and our identified 98 TP candidates belong to completely separate category of stars. It is observed that their IR excess belongs to different ranges. Also TP candidates are high mass candidates with average spectral type around B0-A2, whereas TDCs are lower in mass and possess a spectral type peak at around M4 (Espaillat et al. 2014).

7. Future scope

To the best of our knowledge, this is the first and also the largest study till date to detect and characterize TP candidates. Our study will motivate the community of emission-line star research about the significant need of detecting and studying TP candidates in more detail. Since the disc formation mechanism in CBe stars (known as the 'Be phenomenon') remains poorly understood after more than 150 years of CBe star research, identification and characterization of larger number of TP candidates may shed new lights on the evolutionary phases of various types of emission-line stars. We were unable to conduct spectroscopic investigation on our samples since spectra are currently unavailable for the majority of TP candidates. As a result, we want to perform such a study for our newly identified sample of TP candidates in future utilizing high resolution spectra. Spectroscopic investigations of TP candidates, as well as the comparison of their spectral features with that of CBe and HAeBe stars, will aid in the comprehension of their disc properties.

We have proposed observation programs with facilities such as the 2.34-m Vainu Bappu Telescope (VBT), operated by the Indian Institute of Astrophysics (IIA, Bangalore) and located at Vainu Bappu Observatory (VBO), Kavalur, Tamil Nadu. Our work is the first step to probe this completely new class of emission-line stars and understand their properties. The acquired knowledge, in turn will provide a better understanding about other types of emission-line stars as well as to comprehend the physics of circumstellar disc in these systems.

References

[1] Alecian, E. et al., (2013). MNRAS, 429, 1027.

[2] Arcos, C., Jones, C. E., Sigut, T. A. A., Kanaan, S., & Cur´e, M., (2017). ApJ, 842, 48.

[3] Banerjee G., Mathew B., Paul K. T., Subramaniam A., Bhattacharyya S., & Anusha, R., (2021). MNRAS, 500, 3926.

[4] Banerjee G., Paul K. T., Mathew B., & Subramaniam A., (2020). Be stars: Messengers of stellar disk physics, MAPANA journal of Sciences, Vol. 19, No. 1, 15.

[5] Bhattacharyya S., Mathew B., Banerjee G., Anusha R., Paul K. T., & Kartha, S. S., (2021). MNRAS, 507, 3660.

[6] Bhattacharyya, S., (2021). MPhil Thesis.

[7] B¨ohm, T., Balona, L. A., (2000). IAU Colloq. 175: The Be Phenomenonin Early-Type Stars, 214, 103.

[8] Boehm, T., Catala, C., (1994). A & A, 290, 167.

[9] Collins, G. W., II (1987). IAU Colloq. 92: Physics of Be Stars, 3.

[10] Cox, A. N., (2000). Allen's Astrophysical Quantities.

[11] Dunkin, S. K., Barlow, M. J., Ryan, S. G., (1997). MNRAS, 286, 604.

[12] Dunkin, S. K., Barlow, M. J., Ryan, S. G., (1997). MNRAS, 290, 165.

[13] Finkenzeller, U., Mundt, R., (1984). A & AS, 55, 109.

[14] Folsom, C. P. et al. 2012, MNRAS, 422, 2072.

[15] Espaillat, C. et al., (2014). Protostars & Planets VI, 497. doi:10.2458/azuuapress 9780816531240-ch022

[16] Hamann, F., Persson, S. E., (1992). ApJS, 82, 285.

[17] Hanuschik, R. W., Hummel, W., Sutorius, E., Dietle, O., & Thimm, G., (1996). A & AS, 116, 309.

[18] Herbig, G. H., (1960). ApJS, 4, 337.

[19] Hern´andez, J., Calvet, N., Bricen˜o, C., Hartmann, L., Berlind, P., (2004). AJ, 127, 1682.

[20] Hillenbrand, L. A., Strom, S. E., Vrba, F. J., & Keene, J., (1992). ApJ, 397, 613.

[21] Kogure, T., & Leung, K. C., (2007). Astrophysics and Space Science Library, 342, 1.

[22] Koornneef, J., (1983). A & A, 500, 247.

[23] Leinert, C. et al., (2004) A & A, 423, 537.

[24] Malfait, K., Bogaert, E., Waelkens, C., (1998). A & A, 331, 211.

[25] Martayan, C., Fr´emat, Y., Hubert, A.-M., et al., (2006). A & A, 452, 273.

[26] Martayan, C., Rivinius, T., Baade, D., Hubert, A.-M., & Zorec, J. (2011). Active OB Stars: Structure, Evolution, Mass Loss, and Critical Limits, IAU Colloq. 272, 242.

[27] Jamialahmadi, N. et al., (2015). 579, 81.

[28] Mathew, B., Subramaniam, A., Bhatt, B. C., (2008). MNRAS, 388, 1879.

[29] Mathew, B., & Subramaniam, A., (2011). Bulletin of the Astronomical Society of India, 39, 517.

[30] Mathew, B., Banerjee, D. P. K., Subramaniam, A., & Ashok, N. M. (2012). ApJ, 753, 13.

[31] Meilland, A., Stee, P., Vannier, M., et al., (2007). A & A, 464, 59.

[32] Mermilliod, J. C., (1982). A & A, 109, 48.

[33] Meeus, G., Waters, L. B. F. M., Bouwman, J., van den Ancker, M. E., Waelkens, C., & Malfait, K., (2001). A & A, 365, 476.

[34] Paul, K. T., (2013). PhD Thesis.

[35] Paul, K. T., Shruthi, S. B., & Subramaniam, A., (2017). JAA,38,6.

[36] Porter, J. M., & Rivinius, T., (2003). PASP, 115, 1153.

[37] Rivinius, T., Carciofi, A. C., & Martayan,C.,(2013). AAPR,21,69.

[38] Skrutskie, M. F., Dutkevitch, D., Strom, S. E., Edwards, S., Strom, K. M., & Shure, M. A., (1990). AJ, 99, 1187.

[39] Slettebak, A., (1982). ApJS, 50, 55.

[40] Strom, K. M., Strom, S. E., Edwards, S., Cabrit, S., & Skrutskie, M. F., (1989). AJ, 97, 1451.

[41] Strom, S., Strom, K., Yost, J., Carrasco, L., & Grasdalen, G., (1972). ApJ, 173, 353.

[42] Struve, O., (1931). ApJ, 73, 94.

[43] The, P. S., de Winter, D., Perez, M. R., (1994). A & AS, 104, 315.

[44] Van den Ancker, M. E., de Winter, D., & Tjin A Djie, H. R. E., (1998). A & A, 330, 145.

[45] van den Ancker, M. E. 2001, NOAO Proposal, 127 [46] Vieira, S. L. A. et al., (2003). AJ, 126, 2971.

[46] Waters, L., & Waelkens, C., (1998). Annual Review of Astronomy and Astro-physics, 36, 233.