

HD 46487 is Now a Classical Be Star

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Abstract We present the first observations of hydrogen line emission detected around the B-type star HD 46487, a well-studied star in the CoRoT field of view. The emission is only evident in the H α line, for which the observed violet-red peak separation (Δv_p) is typical of a Be star with a circumstellar disk. The absence of dust emission from the infrared spectral energy distribution excludes the possibility of a very young star. The star's magnitude ($V = 5.079$) and regular use in the literature for a variety of studies suggests that the line emission had a high probability of being found previously, had it been evident; since such was not the case, we believe that the Be phenomenon for HD 46487 has only very recently "turned on." We therefore recommend that this star be spectroscopically and photometrically monitored to track continued changes to its circumstellar morphology.

1. Introduction

Main sequence and giant B-type stars are often fast rotators. Classical Be stars are universally so, and most are believed to rotate at speeds near critical (Townsend *et al.* 2004). Unlike "normal" B-type stars, however, Be stars experience nonradial pulsational modes that eject matter from the surface, allowing them to form a circumstellar decretion disk at the star's equator (Rivinius *et al.* 2013). It is therefore interesting that stars have become Be stars after decades of appearing normal, or else have ceased to exhibit the Be phenomenon (Chojnowski *et al.* 2015, 2017). In fact, observations of the transition between normal B-type and Be star are becoming quite common; many examples exist in the more than decade-long archive of the Be Star Spectra (BeSS) Database. (BeSS may be accessed online at http://basebe.obspm.fr/basebe/Accueil.php?flag_lang=en) (Neiner *et al.* 2011). With the help of BeSS, data are being collected that illustrate the timescales on which disks build up and decrete, track violet-to-red emission peak separation (VR) variability due to one-armed global oscillations (Okazaki 1991), and variability due to outbursts.

But in spite of this growing collection of data, little is known about why they begin to exhibit emission when they do (Porter and Rivinius 2003). McSwain *et al.* (2009) showed that Be stars rotate faster on average than normal B-type stars, and their near-critical speeds make it easier for Be stars to lose mass to their surroundings. The difference in rotation rate for roughly 75% of Be stars is likely due to the transfer of angular momentum during binary interactions (McSwain and Gies 2005; deMink *et al.* 2013), and evidence suggests that such interactions are most common within the first 100 Myr of the star's life.

HD 46487, unlike many recently discovered Be stars, has been well-studied of late; partly this is because it is a bright source ($V = 5.079$) but also because it resides in the CoRoT field of view, which was targeted for exoplanet discoveries and asteroseismology studies (Auvergne *et al.* 2009). At the time that the CoRoT field of view was being searched for Be stars, HD 46487 was not one, and so was not included in Neiner *et al.* (2005) or Frémat *et al.* (2006). However, other publications

from this time allow us to search for any evidence of extant or forming circumstellar matter in the past couple of decades. Its far-ultraviolet (FUV) spectrum exhibited no resonance lines in 2003, as we might have expected for a Be star (Jo *et al.* 2016; Rountree and Sonneborn 1991). It also showed no evidence of any photospheric pulsation (Lefever *et al.* 2010); photometric variability, due to either periodic variability or outbursts, is a common feature of Be stars (Labadie-Bartz *et al.* 2017; Rivinius 2013). Other more recent uses for HD 46487 in the literature, such as being used as a calibrator in interferometric observations (e.g. Ellerbroek *et al.* 2015), further suggest that the star was still normal until as late as 2013.

Several studies have provided us with fundamental physical parameters. HD 46487 was classified as a B5 Vn star in Abt *et al.* (1990), where the "n" designation suggests broad absorption lines. Its projected rotational speed, $v \sin i$ where i is the inclination angle, is likely between 285–300 km/s (Abt *et al.* 2002; Huang *et al.* 2010). This high speed has lead to a bulging out of the equator, such that the equator has a substantially lower surface gravity than its poles ($\log(g)$ of 3.63 at the equator, compared to 3.95 at the poles (Huang *et al.* 2010)). There is no observed binary companion (Abt *et al.* 1990; Eggleton and Tokovinin 2008; Gullikson *et al.* 2016b). Recent spectra of HD 46487 are reported in Gullikson *et al.* (2016a, 2016b). Presented in these works there is a high-resolution ($R \sim 60,000$) spectrum in the wavelength range 3400–10000 Å taken with the cross-dispersed echelle spectrograph (TS23) at the Harlan J. Smith 2.7-meter telescope (<http://www.as.utexas.edu/mcdonald/facilities/2.7m/cs2.html>) on 2014-01-11, as well as two near-infrared (1.45–2.5 μ m) spectra taken with IGRINS (Park *et al.* 2014) on the same telescope taken on 2014-10-16 and 2015-03-03. These three spectra together cover wavelengths for Balmer, Paschen, and Brackett series hydrogen lines, and would all have clearly exhibited that HD 46487 was an emission-line source, had it been evident.

We present the first known observations, taken in March 2017, of the onset of the Be phenomenon in the well-studied star HD 46487. We will describe our observations and data reduction in section 2, present and analyze our spectra in section 3, briefly discuss the results in section 4, and then conclude in section 5.

2. Observations and data reduction

The Adams Observatory sits atop the IDEA Center science building at Austin College in Sherman, Texas. This facility provides opportunities for research, introductory and advanced astronomy classes, and public star-gazing events. Built by DFM Engineering in 2013, the 0.61-m f/8 Ritchey-Chrétien telescope is used primarily for spectroscopy, photometry, and imaging. Instruments are located at Cassegrain focus.

The spectrograph used for these observations is a long-slit LhiresIII spectrograph designed for commercial sale by Shelyak Instruments. It is a modular spectrograph for which the dispersion grating can easily be switched. Collimation and focusing are performed by the same optic, a simple doublet with f/6.67 and a diameter of 30 mm.

The CCD camera being used is a Finger Lakes Instrumentation (FLI) Microline with a thermoelectric cooler that can reach 60° C below ambient. It contains a back-illuminated e2V 42-10 CCD that is coated for enhanced broadband transmittance (~75–95% quantum efficiency from $\lambda = 3800\text{--}7000\text{\AA}$) and the array of 512×2048 pixels are each $13.5\mu\text{m}$ square. Considering the demagnification of the spectrograph camera, the effective pixel size at the slit mask is $16\mu\text{m}$. We therefore choose a $35\mu\text{m}$ slit as the best resolution match (a $32\mu\text{m}$ slit is not available for sale through Shelyak). The camera and spectrograph can be used to observe stars as faint as $V \sim 10$.

Dispersion with the 2400 gr/mm dispersion grating is 0.168\AA per pixel around 6500\AA , and 0.235\AA per pixel around 4300\AA . The resultant resolutions vary with wavelength. Typically we see resolutions in the range $7,500 \lesssim R \lesssim 9,500$ around $H\gamma$ (4341\AA) and $14,000 \lesssim R \lesssim 20,000$ around $H\alpha$ (6563\AA). With the 1200 gr/mm grating, dispersion is 0.54\AA per pixel in between $\sim 3800\text{\AA}$ and 5000\AA , with the resolution varying between $3,000 \lesssim R \lesssim 4,500$.

A log of observational data, including exposure times and signal-to-noise ratios (SNR), is provided in Table 1. HD 46487 was first observed as a telluric standard for another project, so only a single spectrum was acquired on the first night. Flatfield, dark current, bias, and neon-argon lamp images are observed every night. The gain and read noise are computed using the bias and flatfield images; gain is $1.5 e^-/\text{ADU}$ and read noise is $13.1 e^-/\text{pixel}$. Dark current and bias are removed from the science images, and they are then divided by the normalized flatfield. All data reduction and spectral extraction is performed in PYTHON using the author's own routines.

The reduced science images are collapsed in the wavelength direction, and the star's dispersion is fit with a Gaussian to determine an extraction center and width. The spectrum is then extracted between 2σ of the Gaussian's center, rounded out to

Table 1. HD 46487 observations data.

MJD	Dispersion ($\text{\AA}/\text{pixel}$)	Wavelength Range (\AA)	Exposure Time (seconds)	Airmass	Average SNR
57826.098	0.168	6380–6722	1800	1.3	196
57827.054	0.168	6380–6722	1800	1.2	151
57827.103	0.235	4182–4673	1800	1.3	339
57827.141	0.543	3820–4942	900	1.4	304

the nearest pixel. The pixels on either side of the spectrum's extraction window are used to compute a local sky value that is then subtracted away from the star's spectrum, removing any background. Wavelength values are determined using known lines from the neon-argon lamp spectrum. The SNR is computed at every pixel using the CCD equation from Merline and Howell (1995), and are then propagated to compute errors at every wavelength value in the spectrum.

3. Analysis

3.1. Disk emission

The $H\alpha$ spectrum of HD 46487 is shown in Figure 1, as it was observed on the nights of 13 and 14 March 2017. There are noticeable differences between the two spectra. The telluric absorption features are substantially stronger in the second observation. The hydrogen emission is markedly more pronounced as well. Variations in emission strength on the order of days is not uncommon for Be stars, particularly during a phase of disk build-up (e.g. Rivinius *et al.* (2013) and references therein).

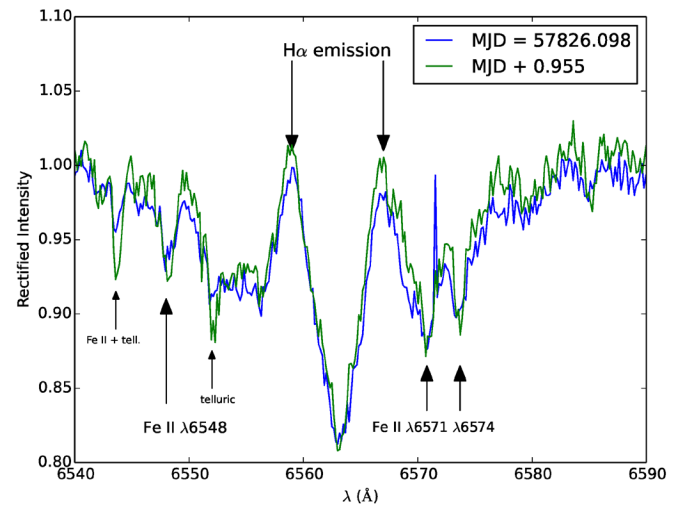


Figure 1. Two spectra observed on consecutive nights show $H\alpha$ emission inside the photospheric absorption line. Various Fe II lines are evident, as well as some telluric absorption lines. Modified Julian dates are shown.

The peak separation in the $H\alpha$ emission is $\sim 7.9\text{\AA}$, which translates to an orbital speed of ~ 180 km/s. If we take $v \sin i = 290$ km/s as a rough average of the available literature values (see section 1), then according to Huang's Law (Huang 1972):

$$r_d = \left(\frac{2 \times v \sin i}{\Delta v_p} \right)^2 \quad (1)$$

where Δv_p is the emission peak separation, then the $H\alpha$ line-emitting radius is $19 R_*$.

3.2. Spectral typing

The optical spectrum of HD 46487 in the wavelength range $3820\text{--}4950\text{\AA}$ is shown in Figure 2 at two resolutions. The strengths of the He I $\lambda 4009/4026$ lines, the presence of Si II $\lambda 4128\text{--}4130$, its strength relative to He I $\lambda 4121, 4144$, and the He I $\lambda 4471/\text{Mg II } \lambda 4481$ ratio all confirm a spectral type of B5.

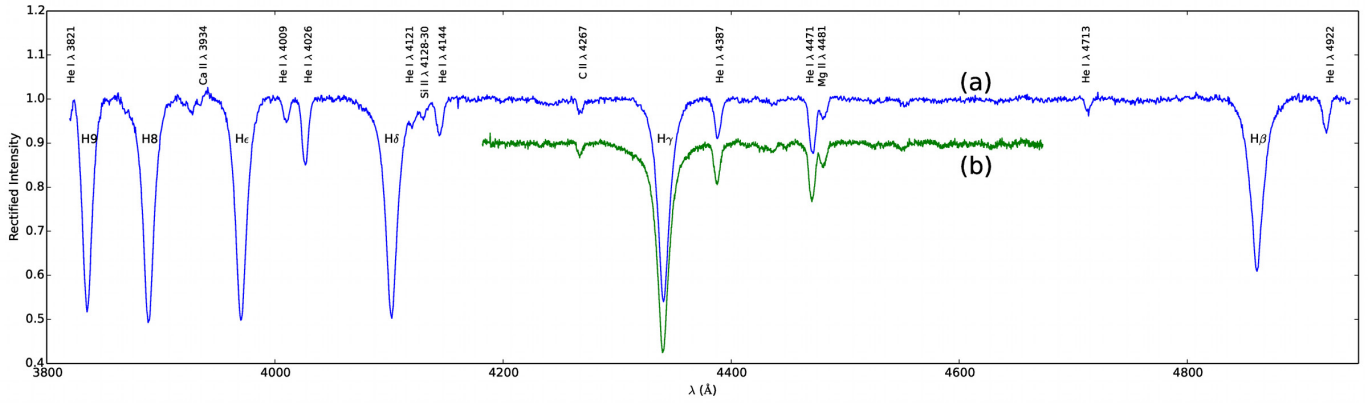


Figure 2. The violet-blue-green spectrum of HD 46487 taken on the night of 14 March 2017, with hydrogen, He I, and various metal absorption lines labeled. Spectrum (a) was obtained using the 1200 gr/mm dispersion grating, ($R \sim 4,000$) while spectrum (b) was obtained using the 2400 gr/mm grating ($R \sim 9,000$).

Table 2. Equivalent width measurements.

Line Identification	Low-res ^a	Equivalent Widths (mÅ)		
		Med-res ^b	B2V ^c	B5V ^c
He I $\lambda 4009$	324 ± 19	—	613	217
He I $\lambda 4026$	977 ± 20	—	1541	878
He I $\lambda 4144$	524 ± 20	—	765	322
C II $\lambda 4267$	144 ± 13	145 ± 17	270	97
He I $\lambda 4387$	612 ± 16	563 ± 23	950	378
He I $\lambda 4471$	683 ± 33	742 ± 34	1442	667
Mg II $\lambda 4481$	193 ± 33	225 ± 30	198	272

Notes: a. Data taken with the 1200 gr/mm dispersion grating. b. Data taken with the 2400 gr/mm dispersion grating. c. Model values from Frémat *et al.* (2006).

The lines are very broad, suggesting that this is a main sequence star, and that the “nebular” designation is justified. We conclude that the spectral type based on visual inspection is B5 Vn, and that emission is not evident in the optical spectrum.

We measured the equivalent widths for the helium and metal absorption lines observed in the optical spectra. Results are given in Table 2, along with plane-parallel model predictions from Frémat *et al.* (2006) for comparison. Most notably, all of the line equivalent widths would suggest an earlier spectral type than what is visually observed.

3.3. The spectral energy distribution

The spectral energy distribution (SED) from ultraviolet to infrared is plotted against a B5 V stellar template in Figure 3. The stellar template is taken from Castelli and Kurucz (2003). Data points were collected using VizieR and sources include Thompson *et al.* (1978) for the ultraviolet, Crawford *et al.* (1971), and Høg *et al.* (2000) for the optical, and the 2MASS survey (Skrutskie *et al.* 2006), the WISE Survey (Wright *et al.* 2010), the AKARI All-Sky Survey (Ishihara *et al.* 2010), and the IRAS survey (Neugebauer *et al.* 1984) for the infrared. The IRAS data points suffer from a very large point spread function (~ 5 arcmin) and it is no surprise that they contain emission from nearby interstellar gas; this is the source of the discrepancy between the IRAS and WISE data points. There is no evidence of dust emission around HD 46487, and out to $22 \mu\text{m}$, there is no substantial deviation from the stellar Rayleigh-Jeans tail.

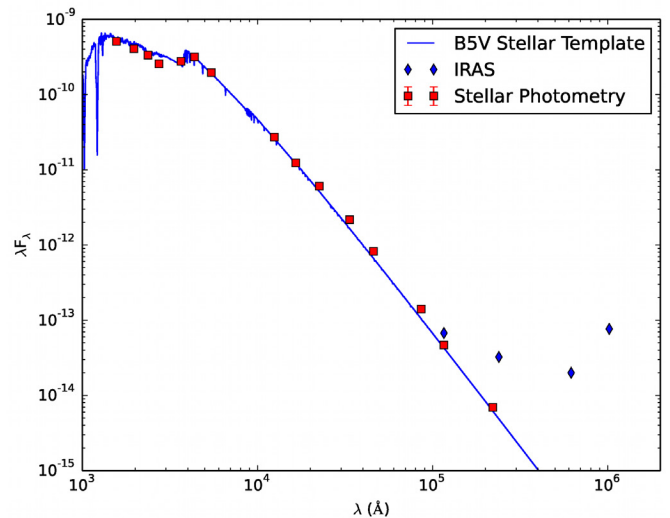


Figure 3. The infrared SED for HD 46487 is plotted against a B5 V stellar template for comparison. IRAS data points (diamonds) have a point spread function that includes nearby diffuse dust emission. Error bars are smaller than the symbol size.

4. Discussion

The H α line-emitting radius is calculated to be $19 R_*$ as discussed in section 3.1. This is consistent with the average H α line-emitting radii for Be stars in Hanuschik (1988) and in Slettebak *et al.* (1992), which quote $\sim 20 R_*$ and $\sim 19 R_*$, respectively.

The spectral type determined upon visual inspection should be treated with skepticism. Fast-rotating stars bulge at the equator, which both increases their surface area and creates a gradient in surface temperature from equator to pole. As a result, fast-rotating stars have higher luminosities and lower average surface temperatures (i.e., later spectral types) than their slow-rotating counterparts (Gray and Corbally 2009). There is also the effect of rotation on the perceived depths of the absorption lines themselves. Fast rotation will broaden the helium and metal absorption lines, so that they appear shallower than they would for another star of the same spectral type. These broadening effects are, in some cases, asymmetric, as is the case with the Mg II $\lambda 4481$ line, which is intrinsically narrower than

the He I $\lambda 4471$ line. The Mg II $\lambda 4481$ /He I $\lambda 4471$ line ratio is one of several used in spectral typing for which intrinsic line width differences can be an issue. Since issues related to rapid rotation affect our perception of a star's intrinsic spectral type, some work has been done to spectral type fast-rotating stars (e.g. Garrison and Gray 1994). At this time, however, there exist no fast-rotating spectroscopic standards earlier than B7 in the literature that can be used for visual comparisons.

The spectral type inferred from equivalent width measurements can also be problematic for Be stars. Continuum emission originating within the disk can partially fill in the absorption lines in a process known as line damping. This means that a Be star's actual spectral type will be earlier than that measured. This is in addition to the effects of scattered light from within the spectrograph itself, which will also fill in absorption signatures. Since the equivalent width measurements in Table 2 already suggest that the spectral type is earlier than what is inferred from visual inspection, we may consider line damping and scattered light as exaggerating effects, and can confidently conclude that HD 46487 has an earlier spectral type (B4 or B3) than is determined from visual inspection.

Pre-main sequence stars such as Herbig Be stars exhibit hydrogen line emission due to a circumstellar disk just like classical Be stars (Herbig 1960). They should additionally possess a broad infrared excess due to circumstellar free-free emission (which is expected for classical Be stars as well; Gehrz *et al.* 1974) and thermally-radiating dust (Malfait *et al.* 1998). Indeed, McDonald *et al.* (2012) found 1 magnitude of infrared excess for HD 46487 out to 22 μm . As illustrated in Figure 3, we cannot confirm such a large infrared excess, and what little infrared excess is seen is certainly not due to dust emission. HD 46487 is therefore not a pre-main sequence source, and what infrared excess exists is most likely due to circumstellar gaseous material and/or winds that would be responsible for free-free emission.

Due to the recent IGRINS and TS23 spectra of HD 46487 published in Gullikson *et al.* (2016b), we can state that HD 46487 was observed to be a normal main sequence B-type star as late as March 2015. All of the data used to compile the SED in Figure 3 was published earlier than 2013. It was additionally used in 2013 as a calibrator for interferometric observations in Bry (Ellerbroek *et al.* 2015), an unsatisfactory choice had it exhibited a substantial gaseous circumstellar disk. It therefore seems likely that the Be phenomenon became evident no earlier than March 2015.

5. Conclusion

HD 46487 ($V = 5.079$) makes an excellent target for small aperture telescopes. Now that it exhibits the Be phenomenon, we should expect it to vary like other Be stars: with periodic photometric variability, the occasional small outburst, and variations in its line emission on timescales anywhere from hours to years. There are three specific areas that will be most useful for continued studies of this source.

Spectroscopic observations of Ha. Such observations would be useful to track the changing line emission, whether it be due to small outbursts and resultant pockets of gas rotating within

the disk, or else long-scale global one-armed oscillations. Spectra submitted to BeSS (as we plan to do) would then be available to the entire community of Be star observers.

Photometric observations at optical wavelengths. Such observations may be useful for tracking periodicity, which is common in Be star atmospheres, and may also be useful for catching outbursts.

Near-infrared photometric observations. Most Be stars show an infrared excess due to free-free emission. Now that HD 46487 exhibits the Be phenomenon, we expect to see this change mostly to its near-infrared SED.

We recognize the need for collaboration on these observations. Interested parties are encouraged to contact the authors.

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