Hybrid star HD 81817 accompanied by brown dwarf or substellar companion

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ABSTRACT

HD 81817 is known as a hybrid star. Hybrid stars have both cool stellar wind properties and Ultraviolet (UV) or even X-ray emission features of highly ionized atoms in their spectra. A white dwarf companion has been suggested as the source of UV or X-ray features. HD 81817 has been observed since 2004 as a part of a radial velocity (RV) survey program to search for exoplanets around K giant stars using the Bohyunsan Observatory Échelle Spectrograph at the 1.8 m telescope of Bohyunsan Optical Astronomy Observatory in Korea. We obtained 85 RV measurements between 2004 and 2019 for HD 81817 and found two periodic RV variations. The amplitudes of RV variations are around 200 m s⁻¹, which are significantly lower than that expected from a closely orbiting white dwarf companion. Photometric data and relevant spectral lines were also analyzed to help determine the origin of the periodic RV variations. We conclude that 627.4-day RV variations are caused by intrinsic stellar activities such as long-term pulsations or rotational modulations of surface activities based on Hβ equivalent width variations of a similar period. On the other hand, 1047.1-day periodic RV variations are likely to be caused by a brown dwarf or substellar companion, which is corroborated by a recent Guía proper motion anomaly for HD 81817. The Keplerian fit yields a minimum mass of 27.1 M⊙, a semimajor axis of 3.3 AU, and an eccentricity of 0.17 for the stellar mass of 4.3 M⊙ for HD 81817. The inferred mass puts HD 81817 b in the brown dwarf desert.

Key words. stars: individual: HD 81817

1. Introduction

Hybrid stars exhibit both emission features in the high-energy regime (Ayres 2005) as well as cool stellar wind feature emission lines near 1500 Å (Hartmann et al. 1980). These objects were first discovered by Hartmann et al. (1980) and more hybrid stars have been found subsequently (Hartmann et al. 1981; Reimers 1982, 1984; Haisch et al. 1992; Reimers & Schmitt 1992). The origin of the X-ray emission of some hybrid stars such as α Per (Ayres 2011) and γ Dra (Ayres et al. 2006) is suspected to be unresolved foreground or background sources.

HD 81817 was suggested to be a hybrid star by Reimers (1984) based on the flux distribution in International Ultraviolet Explorer (IUE) Ultraviolet (UV) spectra. The UV spectra show strong emission lines, almost these emission lines are similar to those of another hybrid star, θ Her (HD 163770). Owing to an apparent UV continuum feature, Reimers (1984) furthermore suggested that HD 81817 is accompanied by a white dwarf with an effective temperature of ~20 000 K. Although HD 81817 is also an X-ray source, Bilíková et al. (2010) suspected that the origin of the X-ray emission is not likely to be a white dwarf companion because the X-ray to bolometric luminosity ratio of HD 81817 falls within the range expected for a K3 III star. Several studies of HD 81817 have been carried out since, but the origin of hybrid chromospheric features in HD 81817 is still unknown.

We have observed HD 81817 over 15.6 yr and compiled 85 high-resolution (R = 90 000) spectra as a part of our program. Since 2003 we have searched for exoplanets around K giants using the radial velocity (RV) method. The RV method is very useful in identifying companions. Compared to main-sequence stars, however, giant stars have various stellar intrinsic mechanisms that can cause similar periodic RV variations such as rotational modulation of inhomogeneous surface features, pulsations, and stellar intrinsic activities. This makes identifying the origins of periodic RV variations in giant stars nontrivial. On the other hand, giant stars also have advantages in that they have many sharp and narrow spectral lines that facilitate precise RV measurements. Besides, giant stars have not been widely studied compare to main-sequence stars to search for exoplanets.

In this paper, we analyze the observed RV variations for HD 81817 and aim to identify their origins. In particular, we explore whether or not this source has a white dwarf companion, which might be an important hint to understand the nature of hybrid stars. Observations and data reduction are described in Sect. 2. In Sect. 3, we analyze the periods of RV measurements of HD 81817 to test the existence of its white dwarf companion. In Sect. 4, we check the photometry and chromospheric activity indices to understand the origin of RV variation periods for HD 81817. In Sect. 5, we analyze the IUE spectra for HD 81817. We summarize our findings in Sect. 6.

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2. Data

2.1. Observations and data reduction

We obtained 85 spectra for HD 81817 from May 2004 to December 2019 using the high-resolution fiber-fed Bohyunsan Observatory Echelle Spectrograph (BOES; Kim et al. 2007) on the 1.8 m telescope at Bohyunsan Optical Astronomy Observatory (BOAO), which can obtain spectrum from 3500 to 10 500 Å with a single exposure. We used a fiber with a diameter of 80 microns that provides a resolution of $R = 90 000$. An iodine ($I_2$) cell was used for precise wavelength calibration. We used the Image Reduction and Analysis Facility (IRAF) package for raw and 1-D data reduction, RV12CELL code (Han et al. 2007) for RV measurements, and Systemic Console (Meschiari et al. 2009) for the analysis and fitting of RV measurements.

2.2. Stellar model

We obtained fundamental photometric parameters such as spectral type, $m_v$, and $B-V$ for HD 81817 from the HIPPARCOS catalog (ESA 1997 and van Leeuwen 2007). We only used the parallax from the Gaia survey (Gaia DR2; Gaia Collaboration 2018) because the stellar atmospheric parameters from Gaia, especially $T_{\text{eff}}$, are very different from other references. We suspect that stellar atmospheric parameters for HD 81817 from Gaia DR2 are not reliable. Andrae et al. (2018) shows the color versus temperature relations for Gaia validation data against the estimates of the effective temperatures from the literatures, and there are significant differences of about $\pm 300$ K with other references around 4000 K. Instead of Gaia data, we derived atmospheric parameters such as $T_{\text{eff}}$, [Fe/H], $v_{\text{micro}}$, and $log \, g$ using the online stellar parameter estimator1 (da Silva 2006). Rotational velocity ($v_{\text{rot}} \sin i$) was estimated from the SPTOOL code (Takeda et al. 2002). The effective temperature from Gaia DR2, then the resulting radius and mass are $93 \pm 7.8 \, M_\odot$ and $3.98 \pm 0.6 \, M_\odot$. These values are also consistent with our results within the uncertainties. The stellar parameters of HD 81817 are summarized in Table 1.

3. Radial velocity measurements

3.1. Keplerian fit

Measured RVs from the spectra of HD 81817 are given in Table 2. We calculated the periods of RV variations using Lomb-Scargle periodograms (Scargle 1982). Figure 1 shows the RV measurements and Keplerian fitting curve (solid line) of HD 81817. Lomb-Scargle periodograms of RV show two significant periods, 1047.1 and 627.4 days with the semi-amplitudes of 211.4 m s$^{-1}$ and 198.5 m s$^{-1}$, respectively (top panel of Fig. 1). The orbital parameters from the best-fit Keplerian orbit are listed in Table 3. The residuals of the Keplerian fitting is 77.6 m s$^{-1}$.

3.2. Testing existence of white dwarf companion

Despite the suggestion that HD 81817 has a white dwarf companion, there have been no kinematic studies to prove or disprove the existence of a white dwarf companion. Our RV measurements of HD 81817 show periodic variations and the amplitude for two RV variation periods were around 200 m s$^{-1}$. To test the existence of a white dwarf companion, we calculated the RV variation expected from a white dwarf companion with the typical mass of 0.7 $M_\odot$, which has an orbital period of 15.6 yr (the duration of our observation). The calculated amplitude is about 1.3 $\sin i$ km s$^{-1}$; this value is significantly higher than our observed RV amplitudes, unless $\sin i$ is very small. The inclination of this system should be about 8.8$^\circ$ or less. The probability

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1 http://stev.oapd.inaf.it/cgi-bin/param
for such a small inclination angle is less than 1.2%. In addition, the unprojected rotational velocity of HD 81817 is about 31 km s\(^{-1}\). Considering the spectral type and radius of HD 81817, this value is unrealistic because these stars with this spectral type have much lower rotational velocities, that is, lower than 10 km s\(^{-1}\) (Fekel 1997).

The secular linear change in RV over 15.6 yr is about 2450 m s\(^{-1}\). Although H\(\alpha\) EWs are nontrivial, but essential, for stellar and exoplanetary studies. We analyzed the H\(\alpha\) photometric data and IPPARCOS. Stellar pulsations can produce photometric variations as well as RV variations. If pulsations cause both RV and photometric variations, then the periods of the photometric and RV variations overlap in the Lomb-Scargle periodogram. Considering the large uncertainties in mass estimate, the result is consistent with our Keplerian fit. Therefore, the existence of a substellar companion at \(\sim\) 3 AU for HD 81817 seems secure.

### 4. Origins of RV variations

Determining the origin of observed periodic RV variations in giant stars is nontrivial, but essential, for stellar and exoplanetary studies. We analyzed the HIPPARCOS photometric data and stellar activity indices such as Ca II H lines, bisectors, \(H\), and \(H\) EWs.

#### 4.1. HIPPARCOS photometry

We checked the variation in the photometry data from HIPPARCOS. Stellar pulsations can produce photometric variations as well as RV variations. If pulsations cause both RV and photometric variations, then the periods of the photometric and RV variations overlap in the Lomb-Scargle periodogram. Although HIPPARCOS data were not contemporaneous with our RV measurements, the same periodicities appear both in the Hipparcos photometric and RV variations. If pulsations cause both RV and photometric variations, then the periods of the photometric and RV variations overlap in the Lomb-Scargle periodogram. Although HIPPARCOS data were not contemporaneous with our RV measurements, the same periodicities appear both in the Hipparcos photometric and RV variations.

| Parameter | HD 81817 b |
|-----------|------------|
| \(P\) [days] | 1047.1 \(\pm\) 8.5 |
| \(T_{\text{period}}\) [JD] | 2449 712 \(\pm\) 108 |
| \(K\) [m s\(^{-1}\)] | 211.4 \(\pm\) 16.4 |
| \(e\) | 0.17 \(\pm\) 0.07 |
| \(\omega\) [deg] | 320 \(\pm\) 34 |
| \(\text{rms} [m s^{-1}]\) | 77.6 |
| \(m \sin i\) [M\(_{\text{Jup}}\)] | 27.1 \(\pm\) 2.1 |
| \(a\) [AU] | 3.3 \(\pm\) 0.1 |

![Fig. 2. Phase diagrams of two periods in RV variations for HD 81817.](image-url)

Period of 15.6 yr is at least larger than 0.04 arcsec, which is almost the same as the angular resolution of the Hubble Space Telescope (HST). In the absence of a HST observation on HD 81817, we cannot completely rule out a very distant white dwarf companion with our RV data alone.

Recently, Kervella et al. (2019) has shown that HD 81817 has a companion with a mass of about 124\(^{+97.39}_{-59.97}\) M\(_{\text{Jup}}\) and semimajor axis of 2.67 AU based on Gaia DR2 proper motion anomaly. Considering the large uncertainties in mass estimate, the result is consistent with our Keplerian fit. Therefore, the existence of a substellar companion at \(\sim\) 3 AU for HD 81817 seems secure.
photometry and RV variations of HD 81817. The Lomb-Scargle periodogram does not show any significant periods in the photometric variations that coincide with RV variation periods as shown in Fig. 3 (first and second panels). Thus, RV variations with periods of 1047.1 days and 627.4 days are not accompanied by photometric variations.

4.2. Chromospheric activity

The Ca II H line is a representative indicator of stellar chromospheric activity discovered by Eberhard & Schwarzschild (1913). Chromospheric activities in the star can make strong emission features at the center of the Ca II H line. Figure 4 shows Ca II H lines of the chromospherically active star HD 201091, the Sun, and HD 81817. Our Ca II line profile of HD 81817 is rather noisy, but does not show any prominent core emission features.

We examined other stellar activity indicators, Hα and Hβ EW variations. The bottom panel of Fig. 3 shows the Lomb-Scargle periodogram of Hα and Hβ EW variations for HD 81817. In the periodogram of Hα EW variations, we find a significant period of ∼600 days with a false alarm probability (FAP) of 0.01. We also find a significant period of ∼273 days for Hβ EW variations. However, we do not find any periodicities in the Lomb-Scargle periodograms of other parameters, which seem to be related to the period of ∼273 days for Hβ EW variations. The period of ∼1100 days for Hβ EW variations is the harmonic of the primary period of ∼273 days because it disappears when the primary period is removed. Thus we conclude that Hβ EW variations are not related to the observed RV variations. Based on these activity indicators, we suspect that stellar activities with a period of ∼600 days are likely to be related to the 627.4 days of RV variations.

4.3. Rotational modulation of surface features

4.3.1. Rotational period

Rotational periods of typical giant stars span several hundred days. The rotation of stars with an inhomogeneous surface can produce periodic RV variations. Thus, a comparison of the rotational period against the RV variation period can help determine the nature of observed RV variations. We calculated the rotational velocity $v_{\text{rot}} \sin i$ for HD 81817 using the SPTOOL code (Takeda et al. 2008), which calculates the line broadening by stellar rotation using five elements (V, Ti, Fe, Ni, and Co) in the wavelength range from 6080 to 6090 Å. The calculated projected rotational velocity of HD 81817 is 4.7 km s$^{-1}$, which is very consistent with other references (see Table 1). We estimate that the rotational period of HD 81817 ranges from 801$ \sin i$ days to 1008$ \sin i$ days (68% CL). If we adopt Gaia stellar parameters, however, the rotational period ranges from 898$ \sin i$ days to 1085$ \sin i$ days (68% CL). The probability for $\sin i$ greater than 1047/1085 is less than 7%. Hence, RV variations of period 1047 days are unlikely to be related to the rotational modulation, albeit this is not impossible.

4.3.2. Bisectors

Rotational modulation of surface features like starspots can produce spectral line asymmetries, which can be quantified by bisectors (Hatzes 1996; Hatzes et al. 1998). The bisector velocity span (BVS) is defined as the difference in line centers between the high and low levels of the line profile. Bisector velocity curvature (BVC) is the difference in the velocity span of the upper half and lower half of the line profile. We averaged bisectors of five sharp and narrow absorption lines for HD 81817 (Sc I 6210.6, Fe I 6261.1, Fe I 6546.2, Ca I 6572.8, and Ni I 6767.8 Å).
We checked the Lomb-Scargle periodogram of BVSs and BVCs (third panel of Fig. 3). No significant periods exist that match those of RV variations. We also checked the correlations between two bisector parameters and RV measurements. Figure 5 shows BVSs and BVCs against RV values for HD 81817. There are no correlations between bisectors and RV measurements. Thus we conclude that the rotational modulation of surface features is not the cause of periodic RV variations.

5. Reanalysis of the IUE spectra

Since our analysis of the RV data and Gaia data indicate that the companion to HD 81817 proposed by Reimers (1984) is unlikely to be a closely orbiting white dwarf, the excess flux in the IUE spectrum can either stem from an object in the foreground, background, or in distant orbit, or it can originate in the extended chromosphere of HD 81817. Unfortunately there are no UV spectra of HD 81817 acquired with the HST that would allow for a definite conclusion of this matter. We do, however, want to discuss the latter possibility by providing an example of an evolved star with a significant UV continuum.

For this purpose we downloaded and co-added spectra of HD 81817 and θ Her from the INES archive (Rodríguez-Pascual et al. 1999) and processed these data in the same manner as described by Reimers (1984) (see first and second panel of Fig. 6). In comparison to θ Her, the spectrum of HD 81817 exhibits a clear continuum, which is described well by a white dwarf model (Koester 2010) with an effective temperature of $T_{\text{eff}} = 20 \, 000$ K and a surface gravity of $\log g = 8$, as proposed by Reimers (1984).

The bottom two panels of Fig. 6 show the UV spectra of μ Gem, which is a giant of spectral type M3IIIab that has been observed both by IUE and HST STIS/FUV-MAMA (e.g., Riley 2017). The low-resolution IUE spectrum (third panel) also exhibits a continuum that seems to decline toward longer wavelengths, albeit not in as smooth a fashion as that of HD 81817. The high-resolution spectrum obtained with the HST (bottom panel) reveals that this effect is caused by a combination of a constant flux level of $\approx 10^{-14} \, \text{erg} \, \text{s}^{-1} \, \text{cm}^{-2} \, \text{Å}^{-1}$ with a large number of emission lines when degraded to the lower resolution of IUE. We thus conclude that to differentiate between the white dwarf hypothesis and the chromosphere or wind of HD 81817 as the true origin of the UV continuum, high-resolution UV spectra of HD 81817 are required.

6. Summary

Hybrid stars are rare objects whose spectra have both cool stellar wind properties and UV or even X-ray emission features of highly ionized atoms. HD 81817 was identified as a hybrid star and believed to have a white dwarf companion based on its UV spectra. However, the existence of a white dwarf companion has not been tested with RV observations.

We found two significant periods in RV variations for HD 81817: the FAP of the 1047.1-day period is about $9 \times 10^{-11}$ and that of 627.4-day period about $2.5 \times 10^{-9}$. The observed

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Fig. 5. Correlations between RV measurements and mean values of BVS (filled circles) and BVC (open diamonds). There are no significant correlations.

Fig. 6. Ultraviolet spectra of HD 81817, θ Her, and μ Gem. Top panel: co-added IUE spectra of HD 81817 (observation IDs SWP19602+SWP21111, red line) and a white dwarf model from Koester (2010) with the parameters given by Reimers (1984). Second panel: co-added IUE spectra of θ Her (observation IDs SWP13642+SWP19624). Third panel: IUE spectrum of μ Gem. Bottom panel: HST STIS/FUV-MAMA E140M spectrum of μ Gem. The three spectra (HST observing IDs oc7 × 09020, oc7 × 09030 and oc7 × 09040) were co-added and rebinned with a bin size of 1 Å.

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1. http://sdc.cab.inta-csic.es/ines/index2.html
amplitudes of RV variations for HD 81817 are too small compared to typical amplitudes in RV variations expected from a closely orbiting white dwarf companion.

The Lomb-Scargle periodogram does not show significant periodic photometric variations. We do not find any core emission features at the center of Ca II H line for HD 81817. Analysis of atmospheric activity indicator lines do not show obvious atmospheric activities. However, there is an approximately 600-day period in Hα EW variations, which may be related to the period of 627 days. Thus the 627-day RV variations are likely to be the result of rotational modulation of surface features or of long-period pulsations, while 1047-day RV variations are from an orbiting companion. Recent Gaia proper motion anomaly, which is understood to be a substellar companion at 2.67 AU (Kervella et al. 2019), corroborates the latter conclusion.

Thus we conclude that 1047.1-day RV variations are caused by an orbiting brown dwarf or substellar companion, which has a minimum mass of 27.1 $M_{\text{Jup}}$, a semimajor axis of 3.3 AU, and an eccentricity of 0.17, assuming the stellar mass of 4.3 $M_{\odot}$ for HD 81817. Especially, the inferred mass puts HD 81817 b in the brown dwarf desert (Grether & Lineweaver 2006), spanning from 13 $M_{\text{Jup}}$ to 80 $M_{\text{Jup}}$. The black points are known companions and the diamond is a brown dwarf or substellar companion candidate of HD 81817 b in this work.

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