Astronomy & Astrophysics manuscript no. hd66051_orbit
November 7, 2017

Letter to the Editor

Orbital parameters and evolutionary status of the highly-peculiar binary system HD 66051

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ABSTRACT

Context. The spectroscopic binary system HD 66051 (V414 Pup) consists of a highly-peculiar CP3 (HgMn) star and an A-type component. It also shows out-of-eclipse variability due to chemical spots. This combination allows the derivation of tight constraints for the testing of time-dependent diffusion models.
Aims. We aim at deriving astrophysical parameters, information on age, and an orbital solution of the system.
Methods. We analysed radial velocity and photometric data using two different methods to determine astrophysical parameters and the orbit of the system. Appropriate isochrones were used to derive the age of the system.
Results. The orbital solution and the estimates from the isochrones are in excellent agreement with the estimates from a prior spectroscopic study. The system is very close to the zero-age main sequence and younger than 100 Myr.
Conclusions. HD 66051 is a most important spectroscopic binary system that can be employed to test the predictions of the diffusion theory explaining the peculiar surface abundances of CP3 stars.

Key words. binaries: eclipsing – stars: chemically peculiar – stars individual: HD 66051 – techniques: photometric

1. Introduction

The classical chemically peculiar (CP) stars are early B- to early F-type objects which make up about 10% of upper main-sequence stars. They exhibit peculiar atmospheric compositions that deviate significantly from the solar abundance pattern. Most CP stars are characterized by large excesses (up to several orders of magnitude) of heavy elements like Si, Cr, Hg or the rare-earth elements (Preston 1974). The chemical peculiarities are generally thought to be caused by atomic diffusion (Michaud et al. 1976). In this model, radiative levitation and gravitational settling operate in the stellar atmospheres of slowly-rotating stars. Without the presence of significant convection, most elements sink under the influence of gravity; however, those with absorption lines near the local flux maximum are radiatively driven outward.

The CP stars are commonly divided into four groups (Preston 1974): CP1 stars (the metallic-line or Am/Fm stars), CP2 stars (the magnetic Bp/Ap stars), CP3 stars (the Mercury- Manganese or HgMn stars) and CP4 stars (the He-weak stars). Whereas the CP2/4 stars are characterized by the presence of globally-organized magnetic fields, the CP1/3 stars are generally considered to be non-magnetic or only weakly-magnetic objects (Hubrig et al. 2012).

The CP3 stars, which are relevant to the present investigation, exhibit unusually strong enhancements of Hg and Mn (up to 6 and 3 dex, respectively), increased abundances of elements such as P, Y, Sr and Xe, and depletions of other elements like He, Ni or Al (Castelli & Hubrig 2004). Although CP3 stars show individualistic abundance patterns, the strength of the observed overabundances generally increases with atomic number (Ghazaryan & Alecian 2016). Some CP3 stars exhibit an inhomogeneous distribution of elements on their surfaces, i.e. chemical spots. As the stars rotate, flux is redistributed in these spots, which leads to photometric variability and line profile variations with the rotation period (Briquet et al. 2010).

Recent studies have brought forth additional evidence for the existence of rotational variability in CP3 stars (Morel et al. 2014; White et al. 2017). A similar case to our target star was presented by Strassmeier et al. (2017), who identified complex out-of-eclipse variability in the eclipsing double-lined spectroscopic binary system HSS 348. This variability, which remained stable in shape and amplitude throughout the CoRoT observations, is characterized by four nearly-equidistant minima of different depth. It was found that at least the primary component is a CP3 star, and the authors concluded that the out-of-eclipse variability is due to rotational modulation caused by an inhomogeneous surface distribution of elements.

It has yet to be fully understood why time-dependent diffusion processes are creating significantly different atmospheric compositions in CP3 stars of similar temperature (Urpin 2015). To investigate this topic in more detail and to elucidate the question of which other processes (if any) are at work in the creation of CP3 star anomalies beside atomic diffusion, corresponding data for stars with precise age determination are needed.

Here, we present an important step in this direction with the calculation of orbital parameters and age determination of the eclipsing binary system HD 66051 (V414 Pup). Niemczura et al. (2017) published detailed abundances of this binary system, which consists of a highly-peculiar CP3 primary and an A-type secondary and boasts an orbital period of about 4.75 d. Out-of-eclipse variability with the same period was identified. The unique configuration of HD 66051 allows to study phenomena such as atmospheric structure, mass transfer, magnetic fields, photometric variability and the origin of chemical anomalies observed in CP3 stars and related objects. Furthermore, the study of the system during eclipses allows precise Zeeman–Doppler imaging of the components (Hubrig & Mathys 1995).

From photometric and radial velocity (RV) measurements, we have derived orbital parameters using two different approaches. We conclude that HD 66051 is a young binary system close to the zero-age main sequence and the primary CP3 component is indeed showing a spotty surface. We consider this object a keystone to analyse time-dependent diffusion at very early stages of main-sequence evolution.

2. Observations and Reductions

Photometric observations were acquired at the Remote Observatory Atacama Desert (ROAD) with an Orion Optics, UK Optimized Dall Kirkham 406/6.8 telescope and a FLI 16803 CCD camera. Data were obtained through Astrodon Photometric BVI_C filters. A total number of 2 803, 2 776, and 2 271 (B, V, I_C) observations were taken during a timespan of, respectively, 60, 60, and 37 days. The reductions were performed with the MAXIM DL program[1] and the determination of magnitudes using the LesvePhotometry program[2].

For the determination of RVs, we used spectra of the following instruments:

- High Accuracy Radial velocity Planet Searcher (HARPS) at the ESO La Silla 3.6m telescope in Chile, R ~ 110 000, 3900Å to 6900Å, from the ESO archive;
- HIgh-Dispersion Echelle Spectrograph (HIDES) at the 1.88m telescope of the Okayama Astrophysical Observatory (OAO) in Japan, R ~ 50 000, 4090Å to 7520Å;
- REOSC spectrograph at the 2.15m telescope of CASLEO in Argentina, R ~ 12 000, 4150Å to 5750Å.

The RVs were measured with our own implementation of the two-spectra cross-correlation function (CCF) technique TODCOR (Zucker & Mazeh 1994), with synthetic spectra calculated for the atmospheric parameters and abundances obtained by Niemczura et al. (2017): $T_{\rm eff} = 12\,500$ K, $\log g = 4.0$, $\upsilon \sin i = 27$ km s^{-1} for the primary, and $T_{\rm eff} = 8\,000$ K, $\log g = 4.0$, $\upsilon \sin i = 18$ km s^{-1} for the secondary star. The synthetic spectra were calculated with the ATLAS 9 and SYNTHE codes (Kurucz 2005), ported to GNU/Linux by Sbordone (2005). Atomic data were taken from Castelli & Hubrig (2004) and supplemented for the second and third spectra of the lanthanides with data taken from the Vienna Atomic Line Database (VALD, Kupka et al. 1999) that have originally been presented in the Data on Rare Earths At Mons University database (DREAM, Biémont et al. 1999). Single measurement errors were calculated using a bootstrap approach, as in Hełminiak et al. (2012).

Table 1. Orbital elements and astrophysical parameters of HD 66051. The employed abbreviations are explained in the text.

Parameter	Value
$P_{\rm orb}$ (d)	4.749218
T_0 (HJD)	2452167.867
e	0.0
SMA ($R_\odot$)	20.370(4)
i (deg)	84.7(1)
T_1 (K)	12 500
T_2 (K)	8975(480)
q	0.56(3)
Ω_1	8.50(9)
Ω_2	8.22(7)
M_1 ($M_\odot$)	3.23(22)
M_2 ($M_\odot$)	1.81(13)

3. Results and Discussion

We obtained orbital parameters using two widely different methods, whose results are in excellent agreement. The final results are presented in Table 1.

The *rms* of the fit is significantly larger than the individual RV errors, which suggests that they were under-estimated and did not include possible systematics. We therefore introduced (added in quadrature) a jitter term of 0.42 and 0.82 km s^{-1} for the primary and secondary, respectively. This term compensates for systematics coming e.g. from the rotational broadening, or the surface inhomogeneities. Moreover, since REOSC is the least precise spectrograph of the three instruments involved, its measurements are likely affected by instrumental systematic errors as well. To compensate for this, we have added an additional term of 2.5 km s^{-1} to all REOSC RV errors. With all modified uncertainties, we reached a reduced χ^2 of the fit very close to 1. Finally, we checked the influence of other systematics (such as poor sampling, low number of measurements, pulsations, etc.) on the uncertainties of the output parameters by running a bootstrap analysis with 10 000 iterations. We found that they dominate the fit, and adopted the bootstrap parameter errors as the final ones. Notably, the relative mass uncertainty is still at a very good level of ~1.5 %.

As a first approach, we employed the code V2FIT (Konacki et al. 2010), which utilizes the Levenberg-Marquard minimization scheme. The orbital period was held fixed to the value of 4.749218 d (Niemczura et al. 2017). We fitted the two velocity semi-amplitudes $K_{1,2}$, systemic velocity (velocity of the centre of mass) γ, and the zero-phase $T_{\rm P}$, which for circular orbits is defined as the moment of maximum velocity of the primary star. We also initially set the eccentricity e and argument of periastron ω as free parameters, but found that e is indifferent from zero and kept it fixed in the final solution. The V2FIT also allows to search for the difference of systemic velocities of each

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[1] http://www.diffractionlimited.com/

[2] http://www.dppobservatory.net/

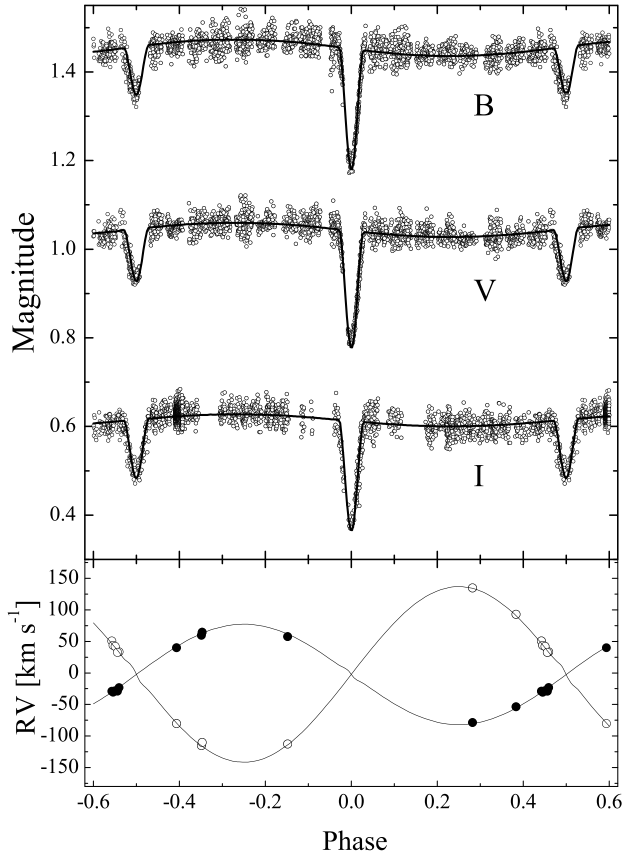

Fig. 1. The fit of the photometric (upper panel) and RV (lower panel) observations with the parameters listed in Table 1.

component $\gamma_2 - \gamma_1$, but we also found it to be insignificant and held it fixed to zero. Finally, we noticed that there is a measurable difference in the zero points between HIDES and REOSC, and we initially set this as a free parameter as well. We assumed a common zero point for HIDES and HARPS, because with only one HARPS spectrum, the difference cannot not be reliably measured, and the HARPS measurements did not deviate significantly from the HIDES measurements.

As a second approach, we used the PHysics Of Eclipsing BinariEs (PHOEBE, Prša et al. 2011) code (version 0.31a). The RV data were analysed with the program RADVEL (Pribulla et al. 2015) which yielded the mass ratio and γ. These two parameters were fixed for the fitting procedure. Furthermore, the values of $a_{1,2}$ sin i gleaned from this program were taken as starting values. The eccentricity was fixed and considered equal to zero. The $T_{\rm eff}$ of the primary component was fixed to 12 500 K according to the results of profile fitting of the Hα and Hβ lines (Niemczura et al. 2017). The $T_{\rm eff}$ of the secondary component was set to a starting value of 8 000 K. A logarithmic law for limb darkening was used, with coefficients interpolated from Van Hamme (1993). Due to the achieved precision of the photometric data, the selection of the limb darkening law did not have any significant impact on the quality of the fit. Values of gravity brightening and albedos for both components were fixed to one because the effective temperatures indicate radiative envelopes for both components.

First, the values for the primary and secondary luminosity levels were set. After that, the surface potentials for both components along with the inclination (i), semi-major axis (SMA), and phase shift were fitted in order to match the eclipse widths of the synthetic and observed light curves. In an iterative process, the inclination and effective temperature of the secondary component were fitted to improve the quality of the fit around the secondary eclipse. The out-of-eclipse curvature of the phase curve with maximum amplitude near phase 0.25 indicates the presence of a large spot positioned perpendicular to the radius vector of the components.

The error estimation in PHOEBE is still somewhat problematic and tends to underestimate errors. The errors of the SMA, i, $T_{\rm eff,2}$ and surface potentials were obtained directly from the differential correction method output. The errors of masses were calculated using $a_{1,2} \sin i$ from RADVEL and the i from PHOEBE.

We used the capability of PHOEBE to fit a spot to the light curve. Our results indicated two solutions with a cool spot on the primary or secondary component, and two solutions with a hot spot on the opposite sides of the components. After a first solution for each scenario, they were improved with the provided fitting methods. We were not able to improve the results by taking into account a spot on the secondary component. However, assuming a spot on the primary component, we were able to significantly improve both solutions which converged to the same result, with the temperature differences ending up the same and the radii of the hot and cool spots being complementary to 180°. The significant Si excess of the primary component implies an optically-bright spot scenario as analogous to magnetic CP2 stars (Oksala et al. 2015). This result is a further important proof that the primary CP3 star exhibits a spotty surface responsible for the detected photometric variability, as suggested by Niemczura et al. (2017).

As a final step, we determined the age of the HD 66051 system using the evolutionary models by Claret (2004) for [Z] = 0.02 and [X] = 0.70. Within these models, the effective temperatures of the more massive stars are corrected for the effects of stellar winds. Convective core overshooting is assumed to be moderate and is modelled with $\alpha_{\rm ov} = 0.20$. The models also take into account binary evolution and were successfully tested and applied to countless binary systems (Eggleton & Yakut 2017).

We employed the spectroscopically-derived astrophysical parameters of both components and their errors (Table 1). First, we used the log $T_{\rm eff}$ and log g values to derive masses from the isochrones. They are in perfect agreement (3.2 and 2.0 M$_\odot$) with the derived values. The system is very close to the zero-age main sequence and not very much evolved. Within the error boxes, we find a maximum age of about 100 Myr or about 10% of the total lifetime on the main sequence.

If we compare these results with the star HD 65949 (Cowley et al. 2010), which is the only other star exhibiting similar chemical peculiarities as our target star, we find that HD 66051 is significantly younger. However, as pointed out, both stars share common elemental anomalies which were interpreted in the light of the common diffusion theory (Michaud et al. 1976; Alecian et al. 2011) by Niemczura et al. (2017). The basic idea is to test the diffusion time scale for certain elements with binary systems such as HD 66051, which allow to put tight constraints on age. To this end, we have to assume that the stars arrive on the main sequence with abundances that are well mixed. Chemical separation then takes place as a result of a time-dependent process. For instance, the deficiency of N and the overabundance of P should develop before the appearance of a significant Mn excess (which is not present in HD 66051). Another point in case is the shared absence of the high Ga abundance typical of many CP3 stars. According to the speculations of Cowley et al. (2010), the Ga anomaly may be a pure diffusion anomaly. It therefore might not have had the time to develop in both stars.

On the other hand, Cowley et al. (2010) have put forth the hypothesis that the composition of HD 65949 might have been influenced by accretion of exotic r-processed material which was subsequently differentiated by atomic diffusion. The suggestion that mass transfer might (also) play a role in the development of chemical peculiarities (in particular in regard to CP3 star anomalies) has been recurring for a long time (Wahlgren et al. 1995). Furthermore, binarity is thought to play a vital role in the development and understanding of CP3 star anomalies (Schöller et al. 2010). With its unique configuration, the system of HD 66051 will allow an investigation of these theories and add constraints on what (if any) processes beside atomic diffusion are at work in the formation of CP3 star anomalies.

For further tests of the time-dependent diffusion models, we need more investigations of spectroscopic binary systems such as HD 66051. This will allow us to add further constraints on the evolution of elemental abundances during the main-sequence lifetime of B-type stars in general. Hopefully, satellite-based missions such as Gaia (Mowlavi et al. 2017) and TESS (Campante et al. 2016) will provide accurate astrometric, kinematic and photometric data for these rare systems. Together with follow-up spectroscopic observations, a detailed analysis will shed more light on the ongoing processes in stellar atmospheres of stars of the upper main sequence.

Acknowledgments

This project was supported by the grant 7AMB14AT030 (MŠMT). KGH acknowledges support provided by Polish National Science Center through grant no. 2016/21/B/ST9/01613. EN acknowledges the Polish National Science Centre grant no. 2014/13/B/ST9/00902.

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