Do the close binaries HD 22128 and HD 56495 contain Ap or Am stars?*

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ABSTRACT

HD 22128 and HD 56495 are both double-lined spectroscopic binary systems with short orbital periods, which have been proposed to host magnetic Ap stars. Ap stars in short-period binary systems are very rare and may provide insight into the origin of magnetism in A-type stars. We study these two systems using high-resolution MuSiCoS spectropolarimetric data, in order to assess the presence of magnetic fields and study the atmospheric chemistry of the components. This represents the first modern magnetic measurements and careful spectroscopic analyses of these stars. We find no evidence of a magnetic field in any of the stars, with precise uncertainties on the longitudinal magnetic field of 50 and 80 G in the components of HD 22128, and 80 and 100 G in the components of HD 56495. We performed detailed abundance analyses of both stars in both systems, finding clear evidence of Am chemical peculiarities in both components of HD 22128, and in the brighter component of HD 56495, with overabundant iron peak elements and underabundant Sc and Ca. The less luminous component of HD 56495 is chemically normal. The atmospheric chemistry is consistent with the absence of magnetic fields, and consistent with the theory of Am star formation proposing that tidal interactions slow the rotation rate of the star, allowing atomic diffusion to proceed efficiently.

Key words: stars: abundances – binaries: spectroscopic – stars: chemically peculiar – stars: magnetic field.

1 INTRODUCTION

Among A- and B-type stars, strong organized magnetic fields are rare, occurring in 5 to 10 per cent of these stars. The chemically peculiar Ap and Bp stars appear to always have such magnetic fields (Arrière et al. 2007), while chemically normal stars, and other classes of chemically peculiar stars, appear to never possess such fields (e.g. Shorlin et al. 2002; Wade et al. 2006; Makaganiuk et al. 2011). An important unresolved question is why strong organized magnetic fields appear in a small subset of A and B stars, and are absent in the majority of A and B stars.

An interesting, and possibly related, observation is that Ap stars are particularly rare in close binary systems. Modern surveys (Gerbaldi, Floquet & Hauck 1985; Carrier et al. 2002) find Ap stars exhibit about the same binary frequency as normal A-type stars (47 ± 5 per cent, Jaschek & Gómez 1970). However, they also identify a clear lack of Ap stars in short-period (i.e. $P_{orb} \leq 3.0$ d) systems (Carrier et al. 2002). This almost certainly provides a clue about the origin of magnetic fields in A and B stars. Consequently, Ap/Bp stars in close binary systems are particularly important systems for detailed investigations. The binarity and magnetic interactions in stars (BinaMicS) collaboration has recently been founded, with the investigation of such systems as one of the primary goals.

While Ap stars appear relatively rarely in short-period binaries, other types of chemically peculiar stars occur in such systems relatively frequently. Am stars occur more commonly in binary systems than normal A stars, and this trend continues to short-period binaries (Abt 1961; Abt & Levy 1985; Carquillat & Prieur 2007). Thus, binary interactions do not inhibit the formation of chemical peculiarities. Indeed, a popular hypothesis is that tidal interactions in binary systems slow the rotation rates of Am stars, thereby reducing mixing from meridional circulation and allowing atomic diffusion to proceed efficiently (Michaud et al. 1983; Abt & Levy 1985). Atomic diffusion is commonly thought to be the physical process giving rise to chemical peculiarities in both Ap and Am stars (Michaud 1970; Michaud, Charland & Megessier 1981).

Systems containing an Ap star and another A star are particularly interesting, since they provide the opportunity to study the incidence of Ap stars in close binaries and also the evolution of magnetic fields and chemical peculiarities in two similar stars. A careful literature review reveals there are only five known or proposed cases of an Ap star in a SB2 binary with a main-sequence A star. HD 55719 was the first well-established system, studied by Bonsack (1976), although

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as a southern object and has not received much modern attention. HD 98088 was established as a binary by Abt (1953) and Abt et al. (1968), and as system with a magnetic Ap star by Babcock (1958). HD 98088 was recently studied in detail by Folsom et al. (2013) who confirm that the primary is an Ap star, find that the secondary is an Am star and present a dipole model of the magnetic field of the primary as well as a detailed abundance analysis. The stars HD 5550, HD 22128 and HD 56495 all show SB2 spectra with an A-type primary (e.g. Carrier et al. 2002); however, the magnetic nature of the proposed Ap component has yet to be definitively established. Two other SB2 systems containing an Ap star are known: HD 135728 (Freyhammer et al. 2008) and HD 59435 (Wade, Mathys & North 1999); however these systems have giants of spectral type G8 as their primary components. All of these stars represent potential targets for intensive observation by the BinaMicS project. This paper focuses on HD 22128 and HD 56495, both of which have been poorly studied but are potentially very interesting Systems.

HD 22128 was first identified as possibly being chemically peculiar by Olsen (1979) based on Strömgren photometry. Abt, Brodziak & Schaefer (1979) classified the star as an Ap star (A9IVp Sr,Eu,Mn st., Ca wk) based on classification resolution spectra. Renson, Gerbal & Catalano (1991) and Renson & Manfroid (2009) included HD 22128 in their catalogue of chemically peculiar stars as an Ap star (A7SrEuMn), but also include a note that the star may be an Am star. There are no magnetic measurements in the literature for HD 22128. Carrier et al. (2002) identified the star as an SB2, and they derived precise orbital parameters which we reproduce here in Table 1. Sowell et al. (2001) made speckle observations of the system, but found no second component down to separations of ~0.2 arcsec, as long as the difference in magnitude between the components is less than 2 mag. Horch et al. (2011) also made speckle observations of the system, finding a similar 0.2 arcsec limit for a difference in magnitude of less than 4.5. This is consistent with the separation found by Carrier et al. (2002), both for their estimated orbital inclination and for all but the most extreme inclinations.

HD 56495 was first reported to be a magnetic A3p star by Babcock (1958), who obtained a marginal magnetic detection of $B_\parallel = +570 \pm 200$ G and a non-detection of $+210 \pm 220$ G. No magnetic measurements have been reported in the literature since. Bertaud (1959) included it as an A3p Sr star in their catalogue of A stars with spectroscopic peculiarities. However, HD 56495 was classified as an Am star by Bertaud & Floquet (1967) (with spectral types A2 from Ca K and F2 from metallic lines), based on classification resolution spectra. Renson, Gerbal & Catalano (1991) and Renson & Manfroid (2009) included HD 56495 in their catalogue of chemically peculiar stars as an Ap star (A7SrEuMn), but also include a note that the star may be an Am star. There are no magnetic measurements in the literature for HD 22128. Carrier et al. (2002) identified the star as an SB2, and they derived precise orbital parameters which we reproduce here in Table 1. Sowell et al. (2001) made speckle observations of the system, but found no second component down to separations of ~0.2 arcsec, as long as the difference in magnitude between the components is less than 2 mag. Horch et al. (2011) also made speckle observations of the system, finding a similar 0.2 arcsec limit for a difference in magnitude of less than 4.5. This is consistent with the separation found by Carrier et al. (2002), both for their estimated orbital inclination and for all but the most extreme inclinations.

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### 2 OBSERVATIONS

Observations of HD 22128 and HD 56495 were obtained with the Multi-Site Continuous Spectroscopy (MuSiCoS) spectropolarimeter, attached to the Telescope Bernard Lyot at the Observatoire du Pic du Midi, France. MuSiCoS, which has since been decommissioned, consists of a Cassegrain mounted polarimeter unit (Donati et al. 1999), attached by optical fibres to a bench mounted cross-dispersed échelle spectrograph (Baudrand & Bohn 1992). The instrument has a resolution of $R = 35 000$ with a wavelength range from 4500 to 6500 Å, and provides polarized Stokes $V$, $Q$ and $U$ spectra as well as total intensity Stokes $I$ spectra. Data reduction was performed with the ESPRIT (Donati et al. 1997) reduction tool, which performs optimal 1D spectrum extraction, as well as the relevant calibrations. The reduced spectra were continuum normalized by fitting a low-order polynomial through carefully selected continuum points, then dividing the observation by the continuum polynomial.

Four observations of HD 22128 were obtained in Stokes $V$ (providing Stokes $I$ as well) in 2004 Feb. For HD 56495, four Stokes $V$ observations were also obtained in 2004, however one of the observations (2004 Feb 9) had very low S/N, due to poor observing conditions, and is discarded in the subsequent analysis. The observations used are reported in Table 2.

### 3 MAGNETIC MEASUREMENTS

In order to investigate the presence of magnetic fields in HD 22128 and HD 56495, Least-Squares Deconvolution (LSD, Donati et al. 1997; Kochukhov, Makaganiuk & Piskunov 2010) was applied to each of the calibrated and normalized spectra. LSD is a cross-correlation technique that produces an ‘average’ line profile, with a much higher S/N than an individual line in the observation. The implementation of LSD by Donati was used, though the results were checked against our own implementation of the procedure, and found to be fully consistent. Line masks were constructed using the atmospheric parameters and chemical abundances derived in Section 4. Atomic data for the line masks and predicted line depths, were extracted from the Vienna Atomic Line Database (VALD) (Kupka et al. 1999), using an 'extract stellar' request.

In HD 22128, both components have very similar parameters, and thus we can safely use the same mask for both. In HD 56495, the components’ temperatures and photospheric abundances differ somewhat. We therefore constructed separate line masks corresponding to the parameters of the two components of HD 56495. For HD 56495, we tested the influence of different line masks, including using the line mask of the primary for the analysis of the secondary and varying the abundances used for the masks by our uncertainties in abundance. This resulted in an insignificant difference in the results, so ultimately we used a mask corresponding to the primary for the analysis of the primary, and a mask corresponding to the secondary for the analysis of the secondary.

The amplitudes of the LSD profiles are normalized by the mean line depth, and the amplitudes of the V LSD profiles are normalized by the product of the mean depth, wavelength and Landé factor (Kochukhov et al. 2010). For HD 22128, the mean Landé factor is

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**Table 1.** Best-fitting orbital parameters from Carrier et al. (2002).

| HD 22128 | HD 56495 |
|----------|----------|
| $P$ (d)  | 5.085564 ± 0.000070 | 27.37995 ± 0.00080 |
| $e$      | 0.00 (fixed)       | 0.1651 ± 0.00070 |
| $k_0$ (km s$^{-1}$) | 15.30 ± 0.21 | -7.57 ± 0.35 |
| $\omega$ (°) | 224.7 ± 3.2 |
| $K_A$ (km s$^{-1}$) | 68.40 ± 0.37 | 44.30 ± 0.74 |
| $K_B$ (km s$^{-1}$) | 73.69 ± 0.55 | 57.75 ± 0.81 |
| $M_A \sin^i (M_\odot)$ | 0.786 ± 0.012 | 1.641 ± 0.055 |
| $M_B \sin^i (M_\odot)$ | 0.729 ± 0.010 | 1.259 ± 0.044 |
| $a_A \sin i (10^6 \text{ km})$ | 4.784 ± 0.026 | 16.45 ± 0.27 |
| $a_B \sin i (10^6 \text{ km})$ | 5.153 ± 0.038 | 21.44 ± 0.30 |
The mean wavelength is 542.0 nm and the mean line depth is 0.323 of the continuum. For HD 56495, the Landé factors are 1.192 and 1.167, the mean wavelengths are 542.9 and 537.8 nm and the mean line depths are 0.382 and 0.324 of the continuum, for the primary and secondary masks, respectively. The resulting LSD profiles are presented in Table 1, for both Stokes $I$ and $V$.

Radial velocities for the components of the two binary systems were measured from the LSD profiles, for each of our observations. This was done by fitting a Gaussian line profile to the LSD line profile of the relevant component, through $\chi^2$ minimization, and taking the centroid of the best-fitting Gaussian as the radial velocity. In order to estimate an uncertainty on the radial velocity, the process was repeated for several different line masks, and different spacings between points in the extracted LSD profile (varying by $\sim$20 per cent), and the full scatter between these runs was taken as the uncertainty. This attempts to sample the noise in the observation somewhat differently, and also account for any systematics introduced by choice of the line mask. The choice of line mask was the largest contributor to the uncertainty in radial velocity. The only clear systematic trend observed was that using a solar abundance mask for the Am stars produced radial velocities 0.1 or 0.2 km s$^{-1}$ below the velocities from an Am mask. It is possible that an opposite trend occurs for the chemically normal HD 56495 B, but this is not clear due to slightly larger random errors. The details of the Am abundances used in the mask and the line depth cutoff used for the mask had no clear systematic impact. The radial velocities are reported in Table 2.

The Stokes $V$ LSD profiles were searched for a signal of a magnetic field, which would be produced by the longitudinal Zeeman effect. We used the detection criterion of Donati et al. (1997), in which the $V/I_c$ profile is searched for significant deviations from the null profile. A null profile is fit to the observed LSD profile, and the resulting $\chi^2$ is used to estimate the false alarm probability (FAP) of a deviation from the null. A conservative FAP of $<10^{-5}$ is used as the definite detection criteria of a magnetic field, and a marginal detection requires an FAP of $<10^{-3}$. FAPs were measured for all LSD profiles and all of the values were below the marginal detection threshold.

Despite the absence of magnetic detections in the VLSD profiles, we can still measure longitudinal magnetic fields from the profiles and use these to place upper limits on the longitudinal field. We measured the magnetic field using the first-order moment method, described by Rees & Semel (1979). This involves integrating the (continuum normalized) LSD profiles $I/I_c$ and $V/I_c$ profiles about the centres of gravity ($v_0$) in velocity $v$:

$$B_z = -2.14 \times 10^{11} \int \frac{(v - v_0) V(v)}{\lambda z_c} \, dv \int \frac{1 - I(v)}{} \, dv,$$

where the wavelength $\lambda$ (expressed in nm) and the Landé factor $z$ correspond to the weighting values used in computing the LSD profiles, and the measured longitudinal field $B_z$ is in Gauss.

Integration ranges for equation (1) were deduced by eye, to include the complete range of the line profile in $I$. Changing this integration range by 10 per cent typically changes the measured magnetic fields by 0.5$\sigma$, and in some cases up to 1$\sigma$, but in no cases does this convert a non-detection into a detection. The measured longitudinal magnetic fields are unaffected by the continuum of the companion in the SB2 spectra. This is because the continuum that would appear in the numerator and denominator of equation (1) cancels out. However, the uncertainty based on propagating photon noise uncertainties through the equation is larger for the SB2 spectrum.

The measured longitudinal fields are presented in Table 2, all of which are non-detections. In one observation of HD 56495, the two components were completely blended, and a single effective longitudinal field was calculated for the full blended line. For HD 22128 A, we find typical 1$\sigma$ uncertainties of 50 G and for HD 22128 B, the typical uncertainties are 80 G. For HD 56495 A, the typical uncertainties are 80 G and for HD 56495 B, the typical uncertainties are 100 G. Borra & Landstreet (1980) surveyed a large number of magnetic Ap stars, finding longitudinal magnetic fields of several hundred to several thousand Gauss, with typical longitudinal fields in the range 500–1000 G. If such a magnetic field were present in one of the stars in this study, we likely would have detected it well above a 3$\sigma$ level. Aurière et al. (2007) studied the Ap stars with the weakest magnetic fields, finding the weakest stars in their sample reached 100 G longitudinal fields, but 300 G longitudinal fields were much more typical even among very weak Ap stars. Thus, unless these stars have remarkably weak longitudinal magnetic fields (among the $\sim$15 weakest Ap stars known), we would have detected an Ap-type magnetic field at 3$\sigma$ or better.

4 CHEMICAL ABUNDANCES

We performed a detailed abundance analysis of both components of HD 22128 and of HD 56495. We did this by directly fitting
the binary spectra of the two systems. Synthetic spectra were produced with the ZEEMAN spectrum synthesis program (Landstreet 1988; Wade et al. 2001), which solves the polarized radiative transfer equations assuming Local Thermodynamic Equilibrium (LTE). Optimizations to the code for stars with negligible magnetic fields were used (Folsom et al. 2012), since we do not detect magnetic fields in these stars. The observed spectra were iteratively fit using a Levenberg–Marquardt $\chi^2$ minimization routine. Input atomic data for ZEEMAN were extracted from VALD (Kupka et al. 1999), using an ‘extract stellar’ request, with temperatures matching those we find for the stars. Model atmospheres were computed with ATLAS9 (Kurucz 1993), which produces plane–parallel model atmospheres in LTE, and solar abundances were used for the calculation of atmospheric structure. A grid of model atmospheres was used, spaced at 250 K in $T_{\text{eff}}$ and at 0.5 in log $g$, and interpolated to produce the models used in the fitting process.

Synthetic binary spectra were created by first computing two single star spectra with ZEEMAN, in absolute flux units. Spectra were then Doppler shifted by their measured difference in radial velocity, and then added together pixel by pixel, weighted by the ratio of stellar radii squared. The summed spectrum was then normalized by the sum of the continuum spectra of the two stars, weighted by the ratio of radii squared. This produces the synthetic binary spectrum. Calculating the spectra in absolute units accounts for the $T_{\text{eff}}$ dependence of luminosity, as well as the variation of the two flux distributions with wavelength. $T_{\text{eff}}$ and $R_A/R_B$ are both parameters determined by the fitting routine.

The fitting proceeded in the same fashion as described by Folsom et al. (2012) and Folsom et al. (2013). The observed SB2 spectra were fit simultaneously for chemical abundances, $v\sin i$ microturbulence, $T_{\text{eff}}$, and the ratio of radii. If this fit produced well-constrained results, as was the case for all windows in this study, we attempted to introduce log $g$ as an additional free parameter, to be fit simultaneously with the above parameters. If this fit was well constrained, and produced sensible results, these results were adopted over previous results that were obtained with a fixed log $g$. A fit was considered to be well constrained if it produced values consistent with other spectral windows, produced consistent best-fitting values for different initial conditions and if the synthetic spectrum matched the observation under visual inspection.

Initial values for $T_{\text{eff}}$ and log $g$ were estimated from Balmer line profiles (H$\alpha$ and H$\beta$), giving initial values for HD 22128 A of $T_{\text{eff}} = 7500$ K and log $g = 4.0$, for HD 22128 B of $T_{\text{eff}} = 6750$ K and log $g = 4.0$, for HD 56495 A of $T_{\text{eff}} = 7500$ K and log $g = 4.0$ and for HD 56495 B of $T_{\text{eff}} = 6250$ K and log $g = 4.0$. These initial estimates were close to the final best-fitting parameters, except for the $T_{\text{eff}}$ of HD 22128 B, which was significantly underestimated. Initially a typical A star microturbulence of 2 km s$^{-1}$ was used for all stars, and solar abundances were initially used for all stars. For HD 22128, $R_A/R_B = 1.2$ was initially used, and for HD 56495, $R_A/R_B = 1.4$ was initially used.

This fitting process for deriving stellar parameters was applied first to one star in the binary, then to the other star in the binary, then repeated. Thus, the fitting process for the full SB2 spectrum proceeded in an iterative fashion, effectively fitting a single star at each step in the process, but ending with a fit to the full SB2 spectrum. The results were checked at each step to ensure good-quality fits to the observation were being achieved and sensible parameters were found. The iterative fitting process continued until consistent results were found for both stars between subsequent iterations. This produced the final best-fit parameters for the binary system in a given spectral window. The same fitting process was used by Folsom et al. (2012) for the SB2 Herbig Be system V380 Ori.

In this abundance analysis, the observation of HD 22128 from 2004 Feb. 9 was used, and the observation of HD 56495 from 2004 Feb 1 was used. These observations were chosen because the components were widely separated in them and they had high S/N. The fitting process, for all stars, was performed on four independent spectral windows. The windows were: 4500–4800 Å, 5000–5500 Å, 5500–6000 Å and 6000–6520 Å. This covers virtually all of the MuSiCoS spectral range, excluding Balmer lines. Sample fits to the observations are presented in Fig. 2. The final best-fitting values were then taken as the average of the best fits from individual windows. Uncertainties were taken as the standard deviation of the best-fitting values from individual windows. For chemical abundances that could only be fit in one or two windows an uncertainty...
was estimated by eye. This estimate included the scatter between lines, noise in the observation and potential normalization errors. The final best-fitting values, and their uncertainties, are presented in Table 3. The best-fitting abundances are plotted relative to the solar abundances of Asplund et al. (2009) in Fig. 3.

The fitting process produced a well-constrained log $g$ for only some spectral windows: three windows in HD 56495 A, all four in HD 56495 B and only one in HD 22128 A and B. For HD 56495, we use the standard deviation of log $g$ from individual windows for the uncertainty in Table 3. For HD 22128, the uncertainty on log $g$ was estimated from the range of values consistent with the Balmer lines and the metallic line fit.

4.1 Chemical abundances of HD 22128 A and B

For HD 22128 A, we find a well-determined $T_{\text{eff}}$ of $7560 \pm 210$ K and a somewhat more uncertain log $g$ of $4.0 \pm 0.5$. For HD 22128 B, we find a very similar $T_{\text{eff}}$ of $7480 \pm 310$ K and log $g$ of $4.0 \pm 0.5$. Through the $\chi^2$-minimization process we also find microturbulences of $3.59 \pm 0.18$ and $3.55 \pm 0.40$ km s$^{-1}$ for HD 22128 A and B, respectively. These values are somewhat greater than usually seen in A stars, but consistent with the elevated values seen in Am stars (e.g. Landstreet et al. 2009). The ratio of radii we find is $R_A/R_B = 1.27 \pm 0.13$, which provides a good fit to the spectra of both stars. Under close inspection, the best-fitting synthetic
Table 3. Best-fitting chemical abundances and stellar atmosphere parameters for both components of HD 22128 and HD 56495. Chemical abundance are in units of log($N_x$/N$_{H\alpha}$), and abundances fit with two or less independent spectral windows are marked with an asterisk (*). Solar abundances are from Asplund et al. (2009).

|       | HD 22128 A | HD 22128 B | HD 56495 A | HD 56495 B | Solar |
|-------|------------|------------|------------|------------|-------|
| $T_{\text{eff}}$ (K) | 7560 ± 210 | 7480 ± 310 | 7800 ± 220 | 6440 ± 170 |       |
| log $g$ | 4.0 ± 0.5 | 4.0 ± 0.5 | 4.0 ± 0.3 | 4.2 ± 0.4 |       |
| $v\sin i$ (km s$^{-1}$) | 19.4 ± 0.9 | 21.0 ± 1.2 | 36.2 ± 1.8 | 14.1 ± 1.3 |       |
| $\xi$ (km s$^{-1}$) | 3.59 ± 0.18 | 3.55 ± 0.40 | 3.44 ± 0.14 | 0.93 ± 0.87 |       |
| $R_k/R_\odot$ | 1.27 ± 0.13 | 1.20 ± 0.10 | 1.28 ± 0.16 | 1.20 ± 0.13 |       |
| C  | −4.05 ± 0.28 | −3.73 ± 0.14 | −3.90 ± 0.36 | −3.43 ± 0.40* | −3.57 |
| O  | −5.24 ± 0.35 | −5.15 ± 0.40* | −5.38 ± 0.30* | −5.95 ± 0.30* | −5.76 |
| Na | −4.44 ± 0.09 | −4.34 ± 0.16 | −4.50 ± 0.27 | −4.60 ± 0.36 | −4.40 |
| Si | −4.34 ± 0.09 | −4.39 ± 0.20 | −4.49 ± 0.15 | −4.68 ± 0.14 | −4.49 |
| S  | −4.38 ± 0.25 | −4.11 ± 0.30* | −4.47 ± 0.30* | −4.88   |       |
| Ca | −6.32 ± 0.19 | −5.90 ± 0.39 | −6.34 ± 0.29 | −5.75 ± 0.31 | −5.66 |
| Sc | −8.99 ± 0.29 | −9.14 ± 0.18 | −10.01 ± 0.40* | −8.79 ± 0.25 | −8.85 |
| Ti | −7.15 ± 0.21 | −7.11 ± 0.39 | −7.14 ± 0.21 | −7.08 ± 0.15 | −7.03 |
| V  | −7.39 ± 0.40* | −6.30 ± 0.18 | −5.96 ± 0.15 | −6.31 ± 0.17 | −6.36 |
| Cr | −5.87 ± 0.17 | −6.21 ± 0.19 | −6.20 ± 0.20* | −6.26 ± 0.42 | −6.57 |
| Mn | −6.13 ± 0.20* | −4.29 ± 0.13 | −4.16 ± 0.19 | −4.51 ± 0.20 | −4.50 |
| Fe | −6.47 ± 0.40* | −5.33 ± 0.15 | −5.14 ± 0.19 | −5.78 ± 0.15 | −5.78 |
| Co | −6.17 ± 0.30* | −7.41 ± 0.30* | −7.78 ± 0.40* | −7.81   |       |
| Cu | −6.51 ± 0.20* | −7.09 ± 0.20* | −7.80 ± 0.66* | −7.44   |       |
| Zn | −8.60 ± 0.24 | −8.88 ± 0.20 | −8.85 ± 0.22 | −9.57 ± 0.40* | −9.79 |
| Y  | −8.45 ± 0.15 | −8.75 ± 0.20 | −8.70 ± 0.34 | −9.42 ± 0.40 | −9.82 |
| Ba | −9.32 ± 0.35* | −9.84 ± 0.50* | −9.34 ± 0.40* |       |       |
| La | −9.16 ± 0.40* | −9.52 ± 0.50* | ≤ −9.5*     |       |       |
| Ce | −9.18 ± 0.30* | −9.52 ± 0.50* | ≤ −9.5*     |       |       |

The close binaries HD 22128 and HD 56495

The abundances are compared with solar values in Table 3. The abundance pattern in HD 22128 B is very similar to HD 22128 A, although slightly less extreme. There are a couple of significant differences. Cr appears to be solar in the secondary but overabundant in the primary. Sc is substantially closer to solar in the secondary than in the primary (by ∼0.7 dex), and Ca is likely closer to solar as well. The strong similarity in chemical abundances likely reflects the similarities in the atmospheric parameters of the stars. The effective temperatures, surface gravities and microturbulences all agree to within 1σ, while $v\sin i$ agrees at slightly over 1σ. Thus, if atomic diffusion is giving rise to the chemical peculiarities in these stars, it is likely proceeding in a very similar fashion in both of them.

4.2 Chemical abundances of HD 56495 A and B

For HD 56495 A, we find $T_{\text{eff}}$ = 7800 ± 220 K and log $g$ = 4.0 ± 0.3 and for HD 56495 B, we find $T_{\text{eff}}$ = 6440 ± 170 K and log $g$ = 4.0 ± 0.4, all of which are well constrained by our metallic line fit. We find a somewhat elevated microturbulence for HD 56495 A of 0.4 dex, while for HD 56495 B, we find a microturbulence of 0.3 dex, which is consistent with that seen in F stars (e.g. Landstreet et al. 2009). We find a ratio of radii $R_k/R_\odot$ = 1.20 ± 0.10, which is consistent with the spectra of both stars. The best-fitting synthetic spectrum matches the observation very well under close inspection, and these results are consistent for all three of our observations of the system in HD 56495 A, we find clear overabundances of iron-peaks elements, Y, Ba and Nd. Ce, Na and S are also marginally overabundant, but very uncertain. Sc is weakly underabundant at −0.3 dex, and Ca may be underabundant, though that is not entirely clear. This star appears to also be an Am star, however not as strongly as HD 22128 A.

The abundance pattern in HD 22128 B is very similar to HD 22128 A, although slightly less extreme. There are a couple of significant differences. Cr appears to be solar in the secondary but overabundant in the primary. Sc is substantially closer to solar in the secondary than in the primary (by ∼0.7 dex), and Ca is likely closer to solar as well. The strong similarity in chemical abundances likely reflects the similarities in the atmospheric parameters of the stars. The effective temperatures, surface gravities and microturbulences all agree to within 1σ, while $v\sin i$ agrees at slightly over 1σ. Thus, if atomic diffusion is giving rise to the chemical peculiarities in these stars, it is likely proceeding in a very similar fashion in both of them.
Figure 3. Abundances relative to solar for HD 22128 A and B (top frame) and HD 56495 A and B (bottom frame), averaged over all spectral windows modelled. Solar abundances are taken from Asplund et al. (2009).

then they would almost certainly be detected. The $T_{\text{eff}}$ we find for HD 56495 B of $6440 \pm 170$ K is substantially cooler than one would expect for an Am or Fm star.

The chemical abundances in HD 56495 A are almost identical to those found in HD 22128 B, and also very similar to those found in HD 22128 A. The abundances of all elements are within uncertainty of the abundances in HD 22128 A, except for Zn which is $2\sigma$ (0.6) dex more abundant in HD 22128 A. The abundances are also all within uncertainty of HD 22128 B, except for Sc which is more abundant in HD 22128 B (by $2\sigma$, 0.9 dex), and Cr which is marginally less abundant in HD 22128 B (by $1.4\sigma$, 0.3 dex). The stellar parameters of HD 56495 A are almost identical to those of HD 22128 A & B. The $T_{\text{eff}}$, $\log g$ and microturbulence are all within uncertainty, though $v\sin i$ is 17 km s$^{-1}$ larger in HD 56495 A. Thus, atomic diffusion is likely acting in a very similar way in all three of these stars.

5 FUNDAMENTAL PARAMETERS

Both binary systems were observed by the Hipparcos satellite, providing precise parallaxes for the systems. From the reduction by van Leeuwen (2007), HD 22128 has a parallax of $6.01 \pm 0.74$ mas ($166 \pm 20$ pc) and HD 56495 has a parallax of $8.71 \pm 0.79$ mas ($115 \pm 10$ pc). Strömgren photometry from Olsen (1994) was used for HD 22128, and from Cameron (1966) for HD 56495 (both obtained from the general catalogue of photometric data of Mermilliod, Mermilliod & Hauck 1997). With this and the bolometric correction from Balona (1994) we can determine the luminosities.
of the stars. This requires the ratio of luminosities of the stars in the systems, which we can calculate from the ratio of \( T_{\text{eff}} \) and ratio of radii squared. The bolometric corrections for the components in each system are very similar. Since the stars are nearby, interstellar extinction was neglected. The uncertainty in luminosity is dominated by uncertainties in the ratio of luminosities and the distance, though uncertainties in the bolometric correction and photometry are included. The luminosities derived are presented in Table 4.

Table 4. Derived fundamental parameters for the HD 22128 and HD 56495 systems.

|          | HD 22128 A | HD 22128 B | HD 56495 A | HD 56495 B |
|----------|------------|------------|------------|------------|
| \( m_v \) | 7.603 ± 0.005 | 7.680 ± 0.013 | 7.603 ± 0.005 | 7.680 ± 0.013 |
| \( d \) (pc) | 166 ± 20 | 115 ± 10 | 166 ± 20 | 115 ± 10 |
| \( T_{\text{eff}} \) (K) | 7560 ± 210 | 7480 ± 310 | 7800 ± 220 | 6440 ± 170 |
| \( L \) (\( L_\odot \)) | 11.9 ± 3.2 | 7.1 ± 2.2 | 6.5 ± 1.2 | 2.1 ± 0.5 |
| \( R \) (\( R_\odot \)) | 2.01 ± 0.29 | 1.58 ± 0.27 | 1.39 ± 0.15 | 1.16 ± 0.16 |
| \( M \) (\( M_\odot \)) | 1.77 ± 0.09 | 1.61 ± 0.09 | 1.67 ± 0.07 | 1.25 ± 0.06 |
| \( \log(\text{age}) \) | 8.95 ± 0.08 | <8.6 | 8.95 ± 0.08 | <8.6 |
| \( v_{\text{rot}} \) (\( \sigma \)) | 49.7 ± 1.2 | 83.8 ± 5.2 | 49.7 ± 1.2 | 83.8 ± 5.2 |
| \( a_{\text{orb}} \) (\( R_\odot \)) | 9.0 ± 0.2 | 9.7 ± 0.2 | 23.8 ± 0.5 | 31.0 ± 0.6 |
| \( \log \, g \) (\( \text{cgs} \)) | 4.08 ± 0.13 | 4.25 ± 0.15 | 4.37 ± 0.10 | 4.40 ± 0.12 |

Figure 4. H–R diagram for HD 22128 and HD 56495. Evolutionary tracks (solid lines) and isochrones (dashed lines) are shown, labelled by mass in solar masses and \( \log \, \text{age} \), respectively. Evolutionary tracks are from Schaller et al. (1992) for standard mass-loss and \( Z = 0.02 \).

but near 90°. We can then use the orbital inclination to derive the semimajor axes of each star’s orbit \( a_{\text{orb}} \), based on the dynamical \( \sin i \) from Carrier et al. (2002). We can also use the derived masses from the H-R diagram and stellar radii from the luminosities and \( T_{\text{eff}} \) to make an alternate measurement of \( \log \, g \). These results are presented in Table 4 and are fully consistent with the spectroscopic \( \log \, g \) values, but have significantly smaller formal uncertainties.

The mass ratios of the stars from the H-R diagram agree well with the dynamical mass ratios of Carrier et al. (2002). For HD 22128 these are \( M_A/M_B = 1.10 \pm 0.08 \) (H-R diagram) and \( M_A/M_B = 0.83 \pm 0.25 \) (dynamical). For HD 56495 they are \( M_A/M_B = 1.30 \pm 0.06 \) (H-R diagram) and \( M_A/M_B = 1.34 \pm 0.03 \) (dynamical). This provides some confidence in the H-R diagram positions of the stars.

Whether the stars are tidally locked was investigated, since they are in very close binary systems. If we assume tidal locking, then the rotational period is equal to the orbital period. This period combined with the stellar radius can be used to derive a hypothetical equatorial rotational velocity. For HD 22128 A, this hypothetical value is 20.0 ± 2.9 km s\(^{-1}\), and for HD 22128 B it is 15.7 ± 2.7 km s\(^{-1}\). For HD 22128 A, the observed \( \sin i \) (19.4 ± 0.9 km s\(^{-1}\)) is consistent with this hypothetical equatorial rotational velocity, thus the star could be tidally locked as long as the rotational axis has an inclination of 76°. However, this would require the rotational and orbital axes to be misaligned by a little over 1°. For HD 22128 B, the observed \( \sin i \) (21.0 ± 1.2 km s\(^{-1}\)) is inconsistent with the hypothetical equatorial value, thus the star is likely not tidally locked. The stellar radius of HD 22128 B would have to be 1.4 times larger for \( \sin i \) to be consistent with tidal locking, which at 2.3σ is unlikely but not impossible. Alternatively, if we assume that the orbital and rotational axes are aligned, we can use \( \sin i \) to estimate the rotational periods. For HD 22128 A, this hypothetical rotational period is 4.0 ± 0.6 d, and for HD 22128 B, it is 2.9 ± 0.5 d. Thus, HD 22128 has probably experienced a large amount of tidal braking, and the system is close to being tidally locked, but does not appear to be actually tidally locked.

We can perform the same evaluation of tidal locking for HD 56495. Assuming that the rotational and orbital periods are equal, the hypothetical equatorial rotational velocities are 2.6 ± 0.3 km s\(^{-1}\) for HD 56495 A and 2.2 ± 0.3 km s\(^{-1}\) for HD 56495 B. These are completely inconsistent with the observed \( \sin i \) for both HD 56495 A (36.2 ± 1.8 km s\(^{-1}\)) and HD 56495 B (14.1 ± 1.3 km s\(^{-1}\)). Alternatively, assuming that the rotational and orbital axes are parallel, we find the hypothetical rotational periods of 1.93 ± 0.24 d for HD 56495 A, and 4.15 ± 0.68 d for HD 56495 B. The \( \sin i \) values are relatively low, and thus the HD 56495 system may have experienced significant tidal braking, but the stars are clearly not tidally locked.

### 6 DISCUSSION AND CONCLUSIONS

Carrier et al. (2002) derived some tentative stellar parameters for HD 22128 and HD 56495, using the assumption that the two components in each system were identical. They used photometry to estimate \( T_{\text{eff}} \), and parallaxes to estimate absolute luminosities. For HD 22128, they found \( T_{\text{eff}} = 6900 \text{ K} \), \( g = 3.65 \), \( \log L/L_\odot = 0.95 \) and \( R/R_\odot = 2.10 \), leading to \( M = 1.99 M_\odot \) and \( i_{\text{orb}} \approx 48° \). These results are consistent with our values at between 1 and 2σ, which is acceptable given the assumptions involved. For HD 56495, they found \( T_{\text{eff}} = 7179 \text{ K} \), \( g = 4.00 \), \( \log L/L_\odot = 0.77 \) and \( R/R_\odot = 1.58 \), leading to \( M = 1.80 M_\odot \) and \( i_{\text{orb}} \approx 75° \). These values are inconsistent with ours, since the components of HD 56495 have
significantly different temperatures and masses, however they do fall between our values, except for radius and mass. A few other large surveys have also derived fundamental parameters for HD 22128 or HD 56495 (e.g. Masana, Jordi & Ribas 2006; Holmberg, Nordström & Andersen 2009; Bailier-Jones 2011; Casagrande et al. 2011); however, they neglected the binary nature of the systems and thus derived inaccurate parameters. Nordström et al. (2004) considered HD 22128 as a spectroscopic binary and found a mass ratio of 0.927 ± 0.005, which is inconsistent with the result of Carri et al. (2002), although this appears to be based on very few radial velocity measurements.

Decin et al. (2003) identified HD 22128 as a main-sequence star with a debris disc, or a Vega analogue, based on an infrared (IR) excess. However, they did not recognize the star as a binary, or an Am star, which brings the result into question. Wyatt et al. (2007) also come to the same conclusion that the star has a debris disc, again not considering binarity and peculiarity, however they note that the system is anomalous and their luminosity or age may have been miscalculated. Since both components of HD 22128 have similar temperatures one would not expect a large IR excess when treated as a single star, so it is possible that there is a debris disc around the system. IR photometry from the Wide-field Infrared Survey Explorer (Wright et al. 2010) shows a far-IR excess for HD 22128, as compared to HD 56495, in the W3 (11.6 μm) and W4 (22.1 μm) bands. The stars agree well in the shorter wavelength W1 and W2 bands, and in the Two Micron All Sky Survey (Cutri et al. 2003) IJK photometry, which lends some support to the presence of a debris disc.

Koen & Eyer (2002) report periodic variability in the Hipparcos photometry of HD 22128. The variability has a period of 0.10545 d and an amplitude of 0.0092 mag. This period is inconsistent with the orbital or any plausible rotational period. However, the period and amplitude are roughly consistent with δ Scuti pulsations. Interestingly, low amplitude δ Sct and γ Dor pulsations appear to occur frequently among Am stars (Balona et al. 2011; Smalley et al. 2011). The interaction between Am chemical peculiarities and pulsations could provide valuable insights into both phenomena.

Since the stars are in close binary systems, and HD 56495 has an orbital inclination approaching 90°, it is worth checking whether the systems could be eclipsing. Using the semimajor axes, stellar radii and inclinations we find HD 22128 could not be eclipsing. HD 22128 would have to have an orbital inclination of ≥ 79° to show a partial eclipse. HD 56495 would not be eclipsing at our best inclination of i_orb = 83.8° but there is enough uncertainty that i_orb could be 90°. Examining the Hipparcos photometry of both systems, phased with their orbital periods, shows no coherent variability. Thus, there is no evidence that either system is eclipsing. This observation places an upper limit on the orbital inclination of HD 56495 of i_orb < 87.8°.

Our magnetic and spectroscopic measurements of HD 22128 strongly indicate that neither component of the system is an Ap star. If a magnetic field typical of an Ap star (maximum B1 typically 500–1000 G; Borra & Landstreet 1980) were present in either star, we almost certainly would have found it. However, the primary of the system is a clear Am star, and the secondary appears to be a somewhat weaker Am star. The symmetry of the lines profiles of both components, and the lack of variability in the spectra other than orbital motions, both support the conclusion that neither star is an Ap star. The stars in the system are close to being tidally locked, but probably are not quite synchronized yet. The classification of HD 22128 as an Ap star rests on the work of Abt et al. (1979), who only had classification resolution spectra. It seems likely that they misclassified the system as an Ap star rather than two Am stars as a consequence of unrecognized binarity, due to low spectral resolution and perhaps an unfortunate orbital phase.

HD 56495 is clearly not an Ap star, based on our spectroscopic and magnetic measurements. If a typical Ap star magnetic field were present in either component it would most likely have been detected. We find the primary of HD 56495 is a clear Am star, and the secondary appears to be a chemically normal F star. The classification of the system as an Ap star rests on the magnetic measurement and spectral classification of Babcock (1958). If the magnetic field of B1 = +4570 ± 200 G reported by Babcock (1958) was present, it is very likely we would have detected it. It is much more likely that Babcock (1958) slightly underestimated the uncertainties, or simply overinterpreted a measurement that is only significant at 2.8σ. Thus, any claims of a magnetic detection are likely spurious. Conversely, the spectroscopic identification of the system as an Am star by Bertaud & Floquet (1967) is correct, at least for the primary.

Our magnetic non-detections are consistent with larger surveys of magnetic fields in Am stars (e.g. Shorlin et al. 2002). A recent study by Aurière et al. (2010) on a sample of 12 Am stars placed very strong limits on the presence of magnetic fields with 1σ uncertainties of 1–3 G. However, Petit et al. (2011) detected the presence of a magnetic field in the Am star Sirius A, with an extremely small longitudinal strength of 0.2 ± 0.1 G. This appears to be similar, at least in strength, to the sub-Gauss field detected in Vega by Lignières et al. (2009). While the magnetic field in Sirius A is likely not dynamically significant, and probably is not important for atomic diffusion, its presence is striking. This poses the question of whether such extremely weak fields are common among Am stars, or A stars in general, or are these unique cases? The presence of such weak fields in HD 22128 and HD 56495 cannot be ruled out by our observations. Regardless, these extremely weak magnetic fields are clearly distinct from those seen in Ap stars.

HD 22128 and HD 56495 represent interesting cases of the development of Am peculiarities from a theoretical standpoint. In HD 22128, the stars are in a very close binary, and thus tidal interactions can easily slow the rotation rates of the star, nearly to the point of synchronization with the orbital period. This reduces meridional circulation, allowing helium settling to occur and atomic diffusion to proceed efficiently, producing Am peculiarities. The two stars have very similar parameters, thus atomic diffusion likely proceeds in a very similar fashion in both stars, producing very similar observed peculiarities. HD 56495 is also a close binary, and thus the stars have likely undergone significant tidal braking, though perhaps not to the same extent as HD 22128 since the system has a wider separation and may be younger. The primary of HD 56495 A has a very similar T_eff and log g to the stars in HD 22128, and displays very similar chemical peculiarities. The secondary of HD 56495 is substantially cooler, falling outside of the typical temperature range of Am or Fm stars, and likely has large enough convection zones to inhibit atomic diffusion. Thus, the chemical abundances seen in these stars can be well explained by the combination of tidal braking and atomic diffusion.

The status of these stars as Am stars, not Ap stars, has an important impact on the incidence of Ap stars in close binaries. Evidently Ap stars are even more rare in close binary systems than previously realized. This leaves only three known or proposed Ap stars in an SB2 system with an A star (HD 55719, HD 98088 and HD 5550) and two more Ap stars in SB2 systems with G giants (HD 59435, HD 135728). The status of HD 98088 as containing an Ap star was
well established by Folsom et al. (2013), and the two systems containing a giant and an Ap were also well established by Wade et al. (1999) and Freyhammer et al. (2008). HD 55719 was established by Bonsack (1976) who made repeated magnetic measurements, however modern observations are warranted. HD 5550 has no magnetic measurements, nor any modern spectroscopic study, and thus is need of new observations to confirm or refute its status as an SB2 system with an Ap star.

The BinaMiC$^2$ collaboration plans a couple follow-up observations of HD 22128 and HD 56495 with the ESPaDOnS spectropolarimeter at the Canada France Hawaii Telescope. These observations should place significantly smaller limits on the magnetic fields of these stars. However, in light of the new results in this paper, they are not likely to be major targets for the BinaMiC$^2$ project. Observations of the other SB2 systems possibly containing Ap stars, as discussed here, are also planned.

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