Contrib. Astron. Obs. Skalnaté Pleso **48**, 139 – 143, (2018)

Constraining the weak-wind problem: an XMM-HST campaign for the magnetic O9.7 V star HD 54879

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Received: September 25, 2017; Accepted: October 10, 2017

Abstract. Mass-loss rates of massive, late type main sequence stars are much weaker than currently predicted, but their true values are very difficult to measure. We suggest that confined stellar winds of magnetic stars can be exploited to constrain the true mass-loss rates $\dot{M}$ of massive main sequence stars. We acquired UV, X-ray, and optical amateur data of HD 54879 (O9.7 V), one of a few O-type stars with a detected atmospheric magnetic field ($B_\mathrm{d} \gtrsim 2\,\mathrm{kG}$). We analyze these data with the Potsdam Wolf-Rayet (PoWR) and XSPEC codes. We can roughly estimate the mass-loss rate the star would have in the absence of a magnetic field as $\log \dot{M}_{B=0} \approx -9.0\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Since the wind is partially trapped within the Alfvén radius $r_\mathrm{A} \gtrsim 12\,R_*$, the true mass-loss rate of HD 54879 is $\log \dot{M} \lesssim -10.2\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. Moreover, we find that the microturbulent, macroturbulent, and projected rotational velocities are lower than previously suggested ($< 4\,\mathrm{km\,s^{-1}}$). An initial mass of $16\,\mathrm{M}_\odot$ and an age of 5 Myr are inferred. We derive a mean X-ray emitting temperature of $\log T_\mathrm{X} = 6.7\,\mathrm{K}$ and an X-ray luminosity of $\log L_\mathrm{X} = 32\,\mathrm{erg\,s^{-1}}$. The latter implies a significant X-ray excess ($\log L_\mathrm{X}/L_\mathrm{Bol} \approx -6.0$), most likely stemming from collisions at the magnetic equator. A tentative period of $P \approx 5\,\mathrm{yr}$ is derived from variability of the Hα line. Our study confirms that strongly magnetized stars lose little or no mass, and supplies important constraints on the weak-wind problem of massive main sequence stars.

Key words: stars: massive – stars: magnetic field – stars: mass-loss

1. Introduction

Massive, late-type main sequence stars are generally known to exhibit mass-loss rates that are orders of magnitude lower than predicted by theory, often referred to as the *weak wind problem* (e.g., Martins et al., 2005; Oskinova et al., 2006). As a consequence of this, typical spectral diagnostics of mass-loss are void of stellar-wind signatures and cannot be used to measure $\dot{M}$ for such stars. However, in the presence of global magnetic fields, stellar winds are confined to stream along to field lines (e.g., ud-Doula & Owocki, 2002), leading to a significant density enhancement that leaves a spectroscopic signature. In our study, we analyze the magnetic O-type star HD 54879. For details, we refer the reader to our recently published study (Shenar et al., 2017, S2017 hereafter).

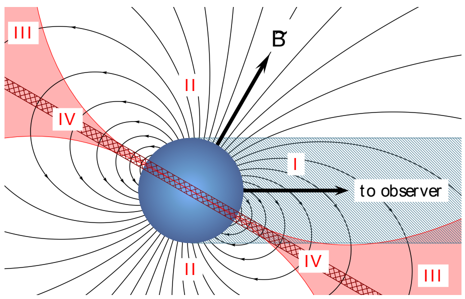

Figure 1. A schematic sketch of a star with a global dipole magnetic field, illustrating the formation regions of different features in the spectrum of HD 54879. See S2017 for details.

The subject of our study, HD 54879, was classified as O9.7 V. Castro et al. (2015) measured a longitudinal magnetic field reaching a maximum of $|B_z| \approx 600$ G for HD 54879, from which they estimated a dipole field of $B_d \gtrsim 2$ kG. The star is believed to reside in the CMa OB1 association, with an estimated distance of $d \approx 1$ kpc (Gregorio-Hetem, 2008). To study HD 54879, we perform a multiwavelength spectral analysis of UV and X-ray spectra acquired by us simultaneously with the *Hubble Space Telescope* (*HST*), and the *XMM-Newton* satellite, complemented by optical HARPS and amateur spectra (see S2017). For the analysis of the UV and optical spectra, we utilize the Potsdam Wolf-Rayet (PoWR) code (Hamann et al., 2006), while the X-ray analysis is performed with the XSPEC software. The combination of X-ray, UV, and optical data is essential, as these spectral ranges probe different regions of the magnetosphere and stellar wind (see Fig. 1).

2. Results

The PoWR code is an established tool for the spectroscopy of massive stars, but relies on the assumption of spherical symmetry, which breaks in the case of magnetic stars. Nevertheless, as we show below, we can derive the photospheric parameters and constrain the wind properties of HD 54879.

2.1. The photosphere

While variability observed in the Hα line is suggestive of a period of $P \approx 5$ yr (Fig. 15 in S2017), no notable variability is observed in photospheric features of HD 54879 along ≈ 6 yr of observing time. We conclude that the impact of the magnetic field on the photosphere is negligible. This is supported by our success to reproduce the majority of the observed photospheric features with our models. The effective temperature $T_{\rm eff}$ is derived from the ratios between lines from different ionization stages (e.g., He I, II, see Fig. 5 in S2017), while the surface gravity g_* is derived from the profiles and strengths of Balmer and

He II lines (see Fig. 4 in S2017). The luminosity and extinction are derived by fitting the observed spectral energy distribution (Fig. 2 in S2017). Overall, the physical parameters are found to be very typical for an O9.7 V star (see S2017 for their full compilation). Two peculiar results involving the photosphere are, however, striking.

Firstly, the macroturbulent ($v_{\rm mac}$), microturbulent (ξ), and projected rotational ($v \sin i$) velocities are found to be much smaller than values reported for other massive stars. In fact, only an upper limit of $4\,{\rm km\,s^{-1}}$ can be derived for all three velocities, since the line widths are dominated by thermal broadening (Fig. 6 in S2017). The low value of $v \sin i$ may very well be due to angular momentum loss via magnetic breaking, but the strength of the magnetic field does not seem to be sufficient to suppress convective motions in sub-photospheric layers of HD 54879 (cf. Sundqvist & Owocki, 2013). The low values of ξ and $v_{\rm mac}$ may therefore be related to the relatively late-type of HD 54879, as late-type massive stars seem to systematically show weaker turbulence (cf. Simón-Díaz et al., 2017).

Secondly, the derived carbon and nitrogen abundances are found to be subsolar by about a factor of three (see Table 2 in S2017), a result also reported by Castro et al. (2015). This stands in contrast to reports of nitrogen enhancements in magnetic B-type stars (Morel et al., 2008). While this result may be explained by a non-homogeneous distribution of the different chemical species over the stellar surface, the lack of photospheric variability does not support this hypothesis.

2.2. The magnetosphere

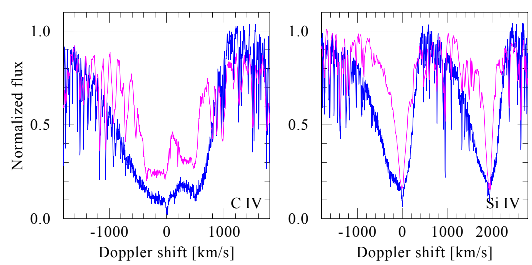

Figure 2. Comparison of normalized *HST* observations of the O9.7 V star HD 36512 (ID: 13346, PI: Ayres, pink solid line) and of HD 54879 (blue solid line)

A comparison of *HST* UV data of the prototypical O9.7 V star υ Ori (HD 36512) with the *HST* data collected for our target, HD 54879, is shown in Fig. 2, where we focus on the two most prominent wind features, the resonance lines C IV $\lambda\lambda 1548, 1551$ and Si IV $\lambda\lambda 1394, 1403$. It is evident that υ Ori shows no, or very little, evidence for a stellar wind, allowing only for an upper-limit of $\dot{M}$ to be derived. In contrast to υ Ori, our target shows a clear asymmetry that is suggestive of absorption stemming from matter surrounding the star. The profiles of HD 54879 have unusually shallow blueshifted edges, suggesting the presence of a large velocity dispersion, reaching a maximum speed of $\approx 1\,000\,\mathrm{km\,s^{-1}}$. Similar line profiles were reported in other studies of magnetic stars (e.g., Nazé et al., 2015).

Solving the full non-LTE radiative transfer in the presence of a magnetic field in 3D is currently not feasible and beyond the scope of this study. Instead, we simulate the motion of the matter along the field lines by a turbulent velocity which is strongly enhanced close above the stellar surface, at $r \approx 1.1\,R_*$. We find the best fit for the combination of $v_{\infty,\mathrm{sph}} = 300\,\mathrm{km\,s^{-1}}$, $\xi_{\mathrm{wind,sph}} = 500\,\mathrm{km\,s^{-1}}$, and $\log \dot{M}_{\mathrm{sph}} = -8.8\,\mathrm{M_\odot\,yr^{-1}}$. X-ray ionization is approximately accounted for in a spherically-symmetric fashion based on our X-ray analysis (see Sects. 3.4 and 5 in S2017). The resulting fit for key diagnostics is shown in Fig. 3. However, because of the false assumption of spherical symmetry, these parameters cannot be assumed to correspond to actual physical parameters. Rather, these parameters serve to reproduce the conditions in the formation region of the resonance lines.

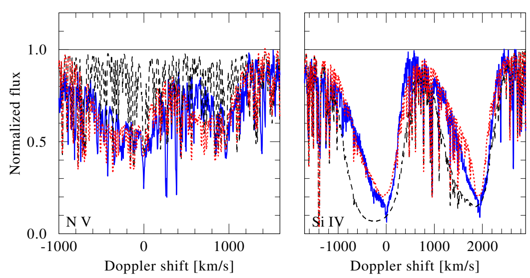

Figure 3. Normalized *HST* observations of HD 54879 (blue solid line) compared to our best-fitting model (red dotted line) and to the same model without the inclusion of X-rays (black dashed line)

By comparing the derived densities to predictions by an analytical model derived for stars with a constant outflow and a global dipole magnetic field (Owocki et al., 2016), we can provide a rough estimate of the mass-loss rate that HD 54879 would have in the absence of a magnetic field, $\dot{M}_{B=0}$. Doing so, we find $\log \dot{M}_{B=0} \approx -9.0\,\mathrm{M_\odot\,yr^{-1}}$. This value, which is expected to represent the mass-loss rate of a *non-magnetic* O9.7 V star, is more than an order of magnitude lower than predicted by theory (Vink et al., 2000), but in line with values reported for other stars of similar spectral type (e.g., Marcolino et al., 2009). From this, we can constrain the Alfvén radius to $r_\mathrm{A} \gtrsim 12\,R_*$. The true mass-loss from the star is then estimated to be $\log \dot{M} \lesssim -10.2\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ (see equations 1-3 of Petit et al., 2017).

3. Summary

We performed a multiwavelength (X-ray to optical) spectral analysis of the object HD 54879, one of about a dozen O-type stars for which a magnetic field was reported. Furthermore, spectroscopic variability of the Hα line was studied. A detailed account of our analysis and results can be found in S2017. Most importantly, we took advantage of the density enhancement caused by the magnetic confinement of the stellar wind to estimate $\dot{M}_{B=0} \approx -9.0\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. This value should represent the mass-loss rate of non-magnetic stars of similar spectral types, but is very difficult to measure in non-magnetic stars. We therefore encourage future studies to further exploit magnetically-confined winds to quantify the poorly-known mass-loss rates of massive main sequence stars.

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