Confirming the oblique rotator model for the extremely slowly rotating O8f?p star HD 108 *

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ABSTRACT

The O8f?p star HD 108 is implied to have experienced the most extreme rotational braking of any magnetic, massive star, with a rotational period $P_{\text{rot}}$ of at least 55 years, but the upper limit on its spindown timescale is over twice the age estimated from the Hertzsprung-Russell diagram. HD 108’s observed X-ray luminosity is also much higher than predicted by the XADM model, a unique discrepancy amongst magnetic O-type stars. Previously reported magnetic data cover only a small fraction (\sim 3.5\%) of $P_{\text{rot}}$, and were furthermore acquired when the star was in a photometric and spectroscopic ‘low state’ at which the longitudinal magnetic field $\langle B_z \rangle$ was likely at a minimum. We have obtained a new ESPaDOnS magnetic measurement of HD 108, 6 years after the last reported measurement. The star is returning to a spectroscopic high state, although its emission lines are still below their maximum observed strength, consistent with the proposed 55-year period. We measured $\langle B_z \rangle = -325 \pm 45$ G, twice the strength of the 2007-2009 observations, raising the lower limit of the dipole surface magnetic field strength to $B_d \geq 1$ kG. The simultaneous increase in $\langle B_z \rangle$ and emission strength is consistent with the oblique rotator model. Extrapolation of the $\langle B_z \rangle$ maximum via comparison of HD 108’s spectroscopic and magnetic data with the similar Of?p star HD 191612 suggests that $B_d > 2$ kG, yielding $t_{\text{S,max}} < 3$ Myr, compatible with the stellar age. These results also yield a better agreement between the observed X-ray luminosity and that predicted by the XADM model.

Key words: Stars : rotation – Stars: massive – Stars : individual : HD 108 – Stars: magnetic fields – Stars: winds, outflows.

1 INTRODUCTION

The rapid spindown of magnetic stars due to angular momentum loss through their magnetized winds has been well-explored theoretically (e.g. Weber & Davis 1967, ud-Doula, Owocki & Townsend 2009). In the case of some rapidly-rotating Bp stars with magnetic, photometric, and spectroscopic observations spanning a long temporal baseline, magnetic braking has been measured directly (e.g. CU Vir, Pyper et al. 1998, Trigilio et al. 2008).

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† E-mail: Mikulášek et al. 2011; σ Ori E, Townsend et al. 2010; HD 37776, Mikulášek et al. 2008, and the inferred timescales are in reasonably good agreement with the predictions of MHD simulations (ud-Doula, Owocki & Townsend 2009). Magnetic braking is expected to increase with both the size of the magnetosphere, and the mass-loss rate. Consistent with this picture, magnetic OB stars are in general more slowly rotating than their non-magnetic kin, with median rotational periods of about 9 days (Petit et al. 2013). Longer rotational periods of weeks and even months are frequently measured. However, there are also cases of extreme rotational braking, with apparent rotational periods on the order of decades. One star in particular is an exemplar of this class: the O8f?p star HD 108, for which evidence from spectroscopy (Nazé, Vreux & Rauw 2001, Nazé et al. 2004) and photometry (Barannikov 2007) indicates a rotational period of between 50 and 60 years (Nazé et al. 2010).
Magnetic measurements of HD 108 were reported by Martins et al. (2010) (hereafter M2010) for the period 2007 to 2009. They found an essentially constant longitudinal magnetic field $\langle B_z \rangle \sim -150$ G, from which a lower limit to the dipole surface magnetic field strength of $B_d > 0.5$ kG was inferred. The lower limit on the spindown timescale, as inferred from a 55 yr rotation period and the lower limit on $B_d$, is $t_{S,\text{max}} = 8.5$ Myr (Petit et al. 2013): this is substantially longer than the age of the star estimated from its position on the Hertzsprung-Russell diagram (HRD), $4 \pm 1$ Myr (M2010). An additional discrepancy is that the star’s X-ray luminosity, thought to originate in magnetically confined wind shocks (Babel & Montmerle 1992; ud-Doula et al. 2014), is almost 1 dex higher than predicted, a unique occurrence amongst magnetic O-type stars for which the opposite is typically the case (Naze et al. 2013). However, the magnetic data cover only a very small fraction ($\sim 3.5\%$) of the star’s presumed rotational cycle. Furthermore, the magnetic data were obtained when the star was at photometric and spectroscopic minimum. In the context of the oblique rotator model in its simplest, dipolar form, this is interpreted as a consequence of the magnetosphere being seen closest to edge-on (Sundqvist et al. 2012; ud-Doula et al. 2013; Wade et al. 2015), corresponding to the rotational phase at which the magnetic equator bisects the stellar disk, and thus $\langle B_z \rangle$ is closest to zero. It is therefore likely that $B_d$ is substantially higher than the lower limit determined by M2010.

In this paper we report a new ESPaDOnS observation of HD 108 that enables new constraints on the stellar rotational period and spindown timescale. In § 2, we describe the observation. In § 3 we examine HD 108’s long-term spectroscopic variability. The magnetic analysis is presented in § 4, and updated magnetic and magnetospheric parameters, including the spindown timescale and predicted X-ray luminosity, are determined in § 5. In § 6 we predict the longitudinal magnetic field variation over the full stellar rotation period, and discuss the implications of this for the star’s magnetic and magnetospheric properties. Conclusions are summarized in § 7.
2 OBSERVATIONS

We obtained two circularly polarized (Stokes V) spectropolarimetric sequences of HD 108 on 2015 September 3 with ESPaDOnS, the high-dispersion (R ~ 65,000) spectropolarimeter mounted at the 3.6 m Canada-France-Hawaii Telescope (CFHT). A detailed description of this instrument is provided by Wade et al. (2016). We followed the same strategy as that adopted by M2010: the measurement consisted of two consecutive spectropolarimetric sequences, each consisting of 4 polarized 1290 s sub-exposures, with a total exposure time of 2.9 h. Each observation yielded four unpolarized (Stokes V) spectra, one Stokes V spectrum, and two diagnostic null N spectra. The data were reduced with the Upena pipeline, which incorporates the automated reduction package Libre-ESpRIT (Donati et al. 1997). The peak SNR per spectral pixel was 802 in the first observation, 933 in the second, and 1325 in the co-added spectrum. We have also downloaded the ESPaDOnS and Narval observations reported by M2010. Narval is a clone of ESPaDOnS mounted at the Bernard Lyot Telescope, and obtains essentially identical results to those of ESPaDOnS (Wade et al. 2016). The SNR of the observations reported in this work are comparable to the mean SNR of 1295 in the nightly ESPaDOnS observations presented by M2010. The spectra were normalized by fitting polynomial splines to the continuum flux in individual orders.

3 VARIABILITY

The left column of Fig. 1 shows a comparison between the line profiles of Hγ, Hβ, and Hα in 2015 vs. 2007-2009. The Balmer lines are much stronger in the 2015 observation, confirming that HD 108 is moving towards a high state. Comparison of the 2015 observation to the Hβ and Hγ variability reported by Nazé, Vreux & Rauw (2001) and the Hα variability reported by M2010 shows that the 2015 data are most similar in appearance to observations collected between 1996 and 1998. As expected, the star’s emission lines are not yet at their most intense: the peak strength of Hβ, last reported in 1987, was approximately 1.65× the continuum, as compared to 1.2× the continuum in the 2015 data.

The right column of Fig. 1 shows the comparison described in the previous paragraph for the He I 447.1 nm line, the C iii and N iii lines near 464 nm, and the He ii 468.6 nm line. We confirm the same pattern of variability as observed by Nazé, Vreux & Rauw (2001); in comparison to the 2008 data, He ii and N iii are essentially unchanged, C iii is noticeably stronger, and He i is much weaker, having been significantly filled by emission.

We measured the following equivalent widths (EWs) from the 2015 data: for Hγ, we found 0.097 ± 0.003 nm; for Hβ, 0.048 ± 0.003 nm; for Hα, 0.533 ± 0.002 nm; and for He i 447.1 nm, 0.065 ± 0.002 nm. While an extended time series of He i EW measurements has not been published, EW time series exist for Hγ, Hβ, and He i 447.1 nm. Fig. 2 shows EW measurements for Hβ, Hγ, and He i 447.1 nm, where we have combined our data with the measurements presented by Nazé, Vreux & Rauw (2001), Nazé et al. (2004), and M2010. The long-term modulation is apparent in all lines, but is especially clear in He i as the H lines show a degree of scatter.

The EW time series confirms the inference from visual comparison of emission lines that the star is in a state similar to that observed in 1998 (HJD ~ 2451000). Assuming the spectroscopic variability to be approximately symmetric about the low state, HD 108 should return to the previously observed maximum emission state in approximately 16 years. This is consistent with the rotation period of ~55 yrs suggested by Nazé et al. (2014). If this period is correct, maximum emission should next be observed in 2036.
4 MAGNETIC FIELD DIAGNOSIS

As a first step in evaluating the star’s magnetic field we performed Least-Squares Deconvolution (LSD; Donati et al. 1997) using the iLSD package developed by Kochukhov, Makaganiuk & Piskunov (2010). We used the two line lists published by M2010 (see their Table 2). The first line list contains 17 spectral lines which were manually selected so as to minimize contamination by the wind. The second line list contains the 5 spectral lines identified as having the smallest blue-shifted absorption with respect to the stellar wind, and thus the absolute minimum of contamination by wind emission. In the following we shall refer to the first list as that containing ‘all’ spectral lines (i.e., all those lines included by M2010), and the second line list as the ‘minimum wind’ line mask. The LSD profiles extracted from the 2015 ESPaDOnS observation with these masks are shown in Fig. 3 where they are compared to the ‘low state’ grand mean LSD profile obtained by combining all LSD profiles extracted from the observations reported by M2010 using the full line list.

The amplitude of Stokes V is noticeably stronger in the most recent observation as compared to the 2007-2009 grand mean, however the Stokes I LSD profile extracted using all lines is much weaker. This suggests that many of the spectral lines included in the larger line mask are in fact significantly affected by the stellar magnetosphere, notwithstanding the attempt by M2010 to select lines with only small contamination with wind emission. Conversely, the Stokes I LSD profile extracted using the minimum wind mask is similar in depth to that of the 2007-2009 ‘low state’ grand mean, indicating that this smaller line mask is largely successful in eliminating wind contamination. The 2015 Stokes V profiles extracted with the two masks are similar, although the minimum-wind mask yields a lower SNR due to the smaller number of included lines. This supports the assumption that Stokes V is unaffected by circumstellar emission, as expected given that the magnetic field should be much stronger at the photosphere than in the circumstellar environment, and confirming the results of M2010 who performed the same comparison.

To evaluate the longitudinal magnetic field \( \langle B_z \rangle \) (e.g. Mathys 1980), we would ideally like to measure \( \langle B_z \rangle \) corresponding as closely as possible to the true photospheric value, thus as far as possible contamination from magnetospheric emission should be avoided. This can be done simply by using the minimum-wind profile, but this sacrifices precision in Stokes V. Instead, we used the LSD profiles extracted using the full line mask, but fixed the Stokes I EW to the maximum EW measured in this dataset. This makes the assumption that all variability in Stokes I is a consequence of the magnetosphere, and that the maximum EW gives the best approximation of the true photospheric line strength. This assumption seems warranted given the much lower level of variability in the minimum wind LSD profiles on either short or long timescales.

These \( \langle B_z \rangle \) measurements are shown as a function of time in the bottom panel of Fig. 4, where they are compared to the EWs, and alone in Fig. 1 where the time axis is zoomed in to show only the epoch spanned by the magnetic data. The weighted mean \( \langle B_z \rangle \) measurement in the 2007-2009 epoch is \(-128 \pm 8\) G, with a standard deviation for individual measurements of \(46\) G (solid and dashed lines in Figs. 2 and 4), close to the mean error bar of \(54\) G. \( \langle B_z \rangle \) in a given year is thus consistent with no variation. The annual weighted mean \( \langle B_z \rangle \) (black squares in Figs. 2 and 4) are suggestive of a slight increase in the strength of \( \langle B_z \rangle \) over time. These results are consistent with those of M2010, confirming that in the 2007-2009 epoch the wind was minimally affecting the lines used for LSD.

![Figure 3](image-url) LSD profiles. We extracted LSD profiles using the full line list used by M2010 (‘all’, blue triangles), and a reduced line list consisting of only those lines with the absolute minimum contamination with emission from the stellar wind (‘MW’, red diamonds). The 2007-2009 grand mean LSD profile is shown for comparison, and was extracted with the full line list. Vertical dotted lines indicate the integration range used for measuring \( \langle B_z \rangle \). The Stokes V and N profiles of the 2015 LSD profiles have been re-binned using a 28.8 km s\(^{-1}\) velocity pixel.

![Figure 4](image-url) \( \langle B_z \rangle \) as a function of time, as in the bottom panel of Fig. 4 but zoomed in to show the epoch spanned by the \( \langle B_z \rangle \) measurements.
In contrast, in 2015 $\langle B_z \rangle = -325 \pm 46$ G, approximately 3 times the strength measured in 2007-2009. If instead we use the minimum wind LSD Stokes V profile to evaluate $\langle B_z \rangle$, $\langle B_z \rangle = -375 \pm 93$ G, which is consistent within error bars. From the LSD Stokes I and V profiles extracted with the full line mask used by M2010, we obtain $\langle B_z \rangle = -643 \pm 107$ G, where the much higher $\langle B_z \rangle$ is a result of the smaller Stokes I EW.

### Table 1. Stellar, magnetic, and rotational parameters

| Parameter          | Quantity | Origin           |
|-------------------|----------|------------------|
| Stellar parameters|          |                  |
| $\log (L_{bol}/L_\odot)$ | 5.7±0.1 | M2010            |
| $T_{eff}$ (kK)     | 35±2     | M2010            |
| $R_\star$ (R_\odot)| 19.4±1.5| M2010            |
| $M_\star$ (M_\odot) | 42±5     | This work        |
| $M_{ZAMS}$ (M_\odot) | 50±3     | This work        |
| Age (Myr)          | 3.3±0.3  | This work        |
| $\log [M/(M_\odot \text{yr}^{-1})]$ | -5.55±0.17 | This work |
| $v_\infty$ (km s$^{-1}$) | 2000±300 | Marcolino et al. (2012) |
| Rotational parameters|         |                  |
| $P_{rot}$ (yr)     | 55       | Nazé et al. (2010) |
| $W$               | (8±1)×10$^{-5}$ | This work |
| $R_K$ (R_\star)    | 560±70   | This work        |
| Magnetic parameters|          |                  |
| $\langle B_z \rangle_{\text{max}}$ (G) | -325±45 | This work       |
| $B_d$ (G)          | ≥1150    | This work        |
| $\eta_*$          | ≥11.5    | This work        |
| $R_A$ (R_\star)    | ≥2.1     | This work        |
| $\tau_1$ (Myr)    | ≤0.5     | This work        |
| $t_{s,\text{max}}$ (Myr) | ≤5     | This work |
| $\log L_{\text{Xobs}}$ (erg s$^{-1}$) | 33.0 | Nazé et al. (2014) |
| $\log L_{\text{XADM}}$ (erg s$^{-1}$) | 33.3±0.4 | This work |

5 MAGNETIC, MAGNETOSPHERIC, AND ROTATIONAL PARAMETERS

HD 108’s stellar, magnetic, magnetospheric, and rotational parameters are summarized in Table 1. The theoretical framework concerning the rotational and magnetic characteristics of stellar magnetospheres has been summarized by Petit et al. (2013), whose development we follow to determine magnetospheric confinement radii, rotation parameters, and spin down timescales.

The lower limit to the dipole magnetic field strength $B_d$ can be inferred from the maximum $\langle B_z \rangle_{\text{max}}$ and the limb darkening coefficient (Preston 1967). According to the tables calculated by Díaz-Cordoves, Claret & Gimenez (1995), a star with HD 108’s $T_{eff}$ and log g should have a limb darkening coefficient of $\sim 0.3$. Using the formula provided by Preston (1967), $B_d \geq 3.5|\langle B_z \rangle|_{\text{max}} = 1150 \pm 160$ G.

The extent of the star’s magnetically confined wind is given by the Alfvén radius $R_A$ (ud-Doula & Owocki 2002). This is determined via a scaling relation with the wind magnetic confinement parameter $\eta_*$, which is the ratio of magnetic to kinetic energy density in the stellar wind.
mass-loss rate. From Eqs. 7 and 8 of ud-Doula & Owocki (2002), we then find \( \eta_t \geq 11.5 \) and \( R_A \geq 2.1 \ R_\odot \).

The corotation or Kepler radius \( R_K \) is determined via the rotation parameter \( W \equiv v_{\text{eq}}/v_{\text{orb}} \), i.e. the ratio of the equatorial velocity to the orbital velocity (ud-Doula, Owocki & Townsend 2008). Assuming \( P_{\text{rot}} = 55 \text{ yr} \), we find \( W \approx (8 \pm 1) \times 10^{-5} \) and \( R_K = 560 \pm 70 \ R_\odot \) (ud-Doula, Owocki & Townsend 2008, Eqs. 11 and 14).

ud-Doula, Owocki & Townsend (2009) provided a scaling relation for the spin-down timescale \( \tau_j \) due to angular momentum loss via the magnetosphere. This scales with the star’s moment of inertia, the (non-magnetic) mass-loss timescale, and \( R_A \). Assuming initially critical rotation, i.e. \( W_0 = 1 \), the maximum spin-down time \( t_{\text{s,max}} \) (i.e. the time required for the star to have decelerated from critical rotation to its current rotation rate) can be estimated from \( \tau_j \) and \( W \). Using \( M, R_A, \) and \( W \) as determined above, we find \( \tau_j \leq 0.5 \text{ Myr} \) \citep{Petit:2013}, and \( t_{\text{s,max}} \leq 5 \text{ Myr} \). This is somewhat higher than the age inferred from the HRD, \( t = 3.3 \pm 0.3 \text{ Myr} \), but is closer than the 8 Myr spin-down age found by \cite{Petit:2013}. If instead the mass-loss rate measured from UV lines by Marcolino et al. (2012) is used, \( t_{\text{s,max}} < 25 \text{ Myr} \), much longer than the main sequence lifetime of the star.

HD 108 has an X-ray luminosity of \( \log \left[ L_X/(\text{erg s}^{-1}) \right] = 33 \) \citep{Naze:2014}, which is overluminous in comparison to similar non-magnetic stars. ud-Doula et al. (2014) developed a semi-analytic scaling relationship that has proven successful in predicting the X-ray luminosities of most magnetic OB stars, although HD 108 was predicted to be about 0.5 dex less luminous than observed \citep{Naze:2014}. Using the lower limit on \( B_\odot \) determined from the new magnetic data, we find that the XADM model predicts \( \log \left[ L_X/(\text{erg s}^{-1}) \right] = 33.3 \pm 0.4 \), consistent with the observed X-ray luminosity. The uncertainty accounts for the uncertainty in \( v_{\infty} \), which strongly affects \( L_X \), and the uncertain efficiency of X-ray production, which may be between 5% and 20% depending on the degree of self-absorption of shock-produced X-rays within the magnetosphere’s cool plasma.

6 DISCUSSION

The wind-sensitive lines of HD 108 show variability on two timescales: a long-term modulation, and short-term variability manifesting as scatter in a given epoch. Similar scatter has been observed in the Hα EWs of the magnetic O stars \( \theta \) Ori C (Stahl et al. 2008), HD 148937 \citep{Wade:2012a}, and CPD –28°2561 \citep{Wade:2013}. This scatter can be qualitatively reproduced in 3D magnetohydrodynamic simulations as a consequence of time-variable structure within the magnetosphere \citep{ud-Doula:2013}. A period search by M2010 on the EWs of variable spectral lines found no stable periods, suggesting stochastic behaviour within the magnetosphere. We performed our own analysis of Hα EW data and have confirmed their conclusion.

The long-term modulation of magnetic O-type star EWs seen in wind sensitive lines is produced by the changing projection of the stellar magnetosphere on the sky. If the rotational and magnetic axes are misaligned, then as the star rotates the angle between the line of sight and the magnetic axis changes. Magnetically confined plasma collects in a disk or torus-like structure in closed loops surrounding the magnetic equator, and corotates with the star. Thus, as the star rotates, the magnetosphere is seen from varying perspectives. When the magnetosphere is closest to face-on, emission strength is at a maximum, whereas when it is seen edge-on, emission is at a minimum. These phases correspond to the magnetic axis being, respectively, closest to parallel or perpendicular to the line of sight, thus also corresponding to maximum and minimum \( B_\odot \).

The magnetic data presented in § 4 indicate that HD 108’s surface magnetic dipole is at least twice as strong as the previously reported lower limit. However, since the star has not yet returned to emission maximum, and since \( \langle B_\odot \rangle \) and emission line EWs tend to correlate, it is likely that \( \langle B_\odot \rangle \) will continue to increase. If this is the case, to estimate the maximum strength of \( \langle B_\odot \rangle \), we used the \( \langle B_\odot \rangle \) and Hβ EWs for HD 191612 (O6-8f?p) which has the most similar stellar parameters to HD 108’s of any other magnetic O-type star \( (T_{\text{eff}} = 36 \pm 1 \text{ kK}, \log L = 5.4 \pm 0.2) \), \( \langle B_\odot \rangle \) of similar magnitude, and complete phase coverage of both \( \langle B_\odot \rangle \) and Hβ \citep{Wade:2011}. We used Hβ rather than the more sensitive Hα lines as HD 108’s Hα time series does not extend to phases of emission maximum. Fig. E shows a linear regression of Hβ EW vs. \( \langle B_\odot \rangle \). The correlation coefficient for HD 191612 is \( r^2 = 0.96 \), indicating a good correlation. HD 108’s measurements fall along this regression line, suggesting that using the regression to extrapolate \( \langle B_\odot \rangle \) is not unreasonable. The dotted line shows HD 108’s Hβ EW at emission maximum; it intersects the regression at \( \langle B_\odot \rangle \sim -550 \text{ G} \), implying that \( B_\odot > 1.9 \text{ kG} \).

While the distribution of surface magnetic dipole

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure6.png}
\caption{Extrapolation of HD 108’s maximum \( \langle B_\odot \rangle \) using Hβ EWs. The dashed line shows a linear regression of HD 191612’s \( \langle B_\odot \rangle \) and Hβ EW measurements (open circles). The blue shaded region indicates the uncertainty in the regression, derived via iterative removal of individual datapoints. HD 108’s measurements are shown by solid red squares. The dotted line shows HD 108’s Hβ EW at emission maximum, and the grey shaded region indicates the mean uncertainty in the EW time series (no uncertainty was provided for the original measurement). This method estimates \( \langle B_\odot \rangle \sim 550 \text{ G} \).}
\end{figure}
strengths amongst magnetic O-type stars ranges from a few hundred G to 20 kG, the majority of such stars have $1 \leq B_\star < 4$ kG (Petit et al. 2013; Wade & MiMeS Collaboration 2015). The 2 kG lower limit obtained from the HD 191612 extrapolation is very close to the centre of the distribution, while the lower limit determined from the previous lower limit. This suggests that HD 108 is unlikely to have a magnetic field stronger than about 4 kG.

Recalculating the magnetospheric parameters and spin-down timescales with the lower limit inferred from HD 191612’s Hβ EWs as the magnetic field strength of HD 108 yields $\eta_\star > 33$, $R_A > 2.7R_\star$, $\tau_1 \leq 0.3$ Myr and $t_{\text{S,max}} \leq 3$ Myr. The upper limit on the maximum spin-down age is approximately the same as the age inferred from the non-rotating evolutionary models of Ekström et al. (2012), $t = 3.3 \pm 0.3$ Myr (Fig. 5). The X-ray luminosity predicted by the XADM model, assuming 10% efficiency, increases to $\log L_X \geq 33.6$, about 0.6 dex higher than the observed X-ray luminosity, and outside the 0.4 dex uncertainty. This difference is small enough that it can be reconciled by reducing the efficiency to 2%, and/or if the X-ray luminosity is rotationally modulated, as has been observed for some O? stars, e.g. HD 191612 for which $\log L_X$ varies by about 0.13 dex throughout a rotational cycle (Nazé et al. 2014). Efficiency is expected to decrease with stronger magnetic confinement, due to the higher density and greater volume of the circumstellar plasma, which absorbs a greater fraction of X-rays (Nazé et al. 2014). HD 108 has stronger emission than any magnetic O-type star but NGC 1624-2, which has by far both the strongest magnetic field and the strongest magnetospheric emission of any magnetic O-type star (Grunhut et al. 2013), and is also the most X-ray underluminous with respect to the XADM model (Nazé et al. 2014). Given this, greater absorption of X-rays by HD 108’s magnetosphere than in those of most other magnetic O-type stars would make sense.

If only one magnetic pole is visible throughout a rotational cycle, the Hα EW will show a single-wave variation, with a single emission maximum at $(B_z)_{\text{max}}$ and a single minimum at $(B_z) \sim 0$ (e.g. HD 191612, and NGC 1624-2; Wade et al. 2011, 2012a). If both magnetic poles are visible, they are likely to be symmetrical about phase 0. In the case of a 110 yr period, there should have been in the vicinity of the observed and reflected $(B_z)$ measurements.

![Figure 7. Extrapolation of HD 108’s (Bz) curve using either a 55 yr period (left) or a 110 yr period (right). Filled circles correspond to annual mean $(B_z)$ measurements, open circles indicate the estimated $(B_z)$ obtained from reflecting $(B_z)$ about phase 0. In the case of a 110-yr period, both magnetic poles must be visible, thus the polarity of the reflected measurements must be reversed. Reflected measurements were used to constrain least-squares sinusoidal fits, indicated by solid curves; dashed curves show the 1σ uncertainty in the fits. The bottom panels show the fit in the vicinity of the new magnetic measurement shows that HD 108’s magnetic field and slow rotation of HD 108 define here using JD0 = 2454000, corresponding to the time of minimum emission (see Fig. 2). For a 55 yr period, $(B_z)$ should be negative at all phases. For a 110 yr period, $(B_z)$ should be positive between phases 0.5 and 1.0, thus, the polarity of the reflected $(B_z)$ estimates reversed.](image)

It may be significant that all $(B_z)$ measurements to date have been negative. For a double-wave variation, emission minimum corresponds to a polarity change in $(B_z)$: thus, if the most recent data had been of positive polarity, the period would have to be 110 years. To explore this further, we calculated least-squares sinusoidal fits to $(B_z)$ using both periods. These are shown in Fig. 7. To help constrain the fits, we estimated $(B_z)$ under the assumption that a sinusoidal $(B_z)$ curve must be symmetrical about phase 0, which we...
within one standard deviation of the centre of the observed $B_d$ distribution of magnetic O-type stars. A 2 kG dipole yields better agreement between the spindown timescale and the stellar age inferred from HD 108’s position on the HRD.

The higher lower limit to $B_d$ also resolves the discrepancy between HD 108’s observed X-ray luminosity and that predicted by the XADM model: HD 108 is now slightly less luminous than predicted by XADM, as is the case for all other magnetic O-type stars. Indeed, bringing the observed and predicted X-ray luminosities into agreement now requires an efficiency of $\sim 2\%$, somewhat less than the 5-10% required for most other magnetic O-type stars. This reduced efficiency may be consistent with the fact that HD 108’s H emission is stronger than any star but NGC 1624-2, implying a larger magnetosphere that absorbs a greater fraction of the X-rays produced by the magnetically confined wind shocks.

The increased rate of change in $\langle B_d \rangle$ between the 2007-2009 epoch, when $\langle B_d \rangle$ was essentially flat, and the 2015 measurement, is more consistent with a single-wave EW variation in which only one magnetic pole is visible. This indicates that the period is likely 55 rather than 110 years.

Further magnetic data will be essential to constraining the star’s surface magnetic field strength. From the EW variation, and assuming a 55 year rotation period, magnetic maximum should next occur in 2036. Until then, a new magnetic measurement should be collected at least once every 5 years, in order to sample the rotational phase curve in increments of at least 0.1. Additional X-ray observations should also be obtained in similar intervals, in order to determine to what degree rotational modulation can explain the discrepancy between observed and predicted X-ray luminosities.

Future spectroscopic data may also be instrumental in distinguishing between 55 yr and 110 yr periods. Unless $i+\beta$ is exactly $180^\circ$, the EW curve will not be perfectly symmetric between times of positive and negative magnetic polarity. Thus, if the next emission maximum (which will correspond to the next magnetic maximum) is substantially stronger or weaker than the previous, this will be good evidence that the period is actually 110 yr, while if the maxima are of the same strength, it will be more likely that $P_{\text{rot}} = 55$ yr. Comparison of observed EW curves to those predicted by MHD models of HD 108’s stellar wind and magnetosphere, as performed for HD 57682 (Grunhut et al. 2012), HD 191612 (Sundqvist et al. 2012), and CPD $-28^\circ 2561$ (Wade et al. 2014), will be helpful in determining the star’s magnetic geometry, as such models can help to constrain the inclination angle. Due to its extremely slow rotation HD 108 also presents an excellent target for spectral monitoring, which could be used to explore the characteristic timescales of turbulent plasma flows within stellar magnetospheres.

The conclusion that HD 108’s spindown age and stellar age are compatible is tentative, as it relies upon evolutionary models that do not account for the effects of magnetic fields on stellar structure. Meynet, Eggenberger & Maeder (2011) explored the impact of rotational braking and the inhibition of mixing on stellar evolution, however a truly self-consistent treatment has yet to be performed. Future models should investigate the inter-relation of mass-loss quenching due to magnetic wind confinement, as well as the decline in the surface magnetic field strength due either to flux conservation in an expanding stellar atmosphere, and/or to magnetic flux decay (Landstreet et al. 2003), these effects have the potential to modify stellar evolution directly, while at the same time, the evolution of the star may have an influence on the magnetic field, and hence on the magnetosphere and magnetic braking. When such models are available, the gyrochronological ages of massive, magnetic stars should be revisited.

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