NGC 1624-2: A slowly rotating, X-ray luminous Of?p star with an extraordinarily strong magnetic field

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Received, in original form

ABSTRACT
This paper presents a first observational investigation of the faint Of?p star NGC 1624-2, yielding important new constraints on its spectral and physical characteristics, rotation, magnetic field strength, X-ray emission and magnetospheric properties. Modeling the spectrum and spectral energy distribution, we conclude that NGC 1624-2 is a main sequence star of mass $M \approx 30 M_\odot$, and infer an effective temperature of $35 \pm 2$ kK and log $g = 4.0 \pm 0.2$. Based on an extensive time series of optical spectral observations we report significant variability of a large number of spectral lines, and infer a unique period of $157.99 \pm 0.94$ d which we interpret as the rotational period of the star. We report the detection of a very strong - $5.35 \pm 0.5$ kG - longitudinal magnetic field $\langle B_z \rangle$, coupled with probable Zeeman splitting of Stokes $V$ profiles of metal lines confirming a surface field modulus $\langle B \rangle$ of $14 \pm 1$ kG, consistent with a surface dipole of polar strength $\geq 20$ kG. This is the largest magnetic field ever detected in an O-type star, and the first report of Zeeman splitting of Stokes $I$ profiles in such an object. We also report the detection of reversed Stokes $V$ profiles associated with weak, high-excitation emission lines of O iii, which we propose may form in the close magnetosphere of the star. We analyze archival Chandra ACIS-I X-ray data, inferring a very hard spectrum with an X-ray efficiency log $L_x/L_{bol} = -6.4$, a factor of 4 larger than the canonical value for O-type stars and comparable to that of the young magnetic O-type star $\theta^1$ Ori C and other Of?p stars. Finally, we examine the probable magnetospheric properties of the star, reporting in particular very strong magnetic confinement of the stellar wind, with $\eta_s \approx 1.5 \times 10^4$, and a very large Alfvén radius, $R_{Alf} = 11.4 R_*$.  

Key words: Stars : rotation – Stars: massive – Instrumentation : spectropolarimetry.
1 INTRODUCTION

The detection (e.g. Grunhut et al. 2009), empirical characterization (e.g. Wade et al. 2011) and theoretical modelling (e.g. Sundqvist et al. 2012) of a growing sample of magnetic O stars is leading to a new, refined picture of the scope and impact of magnetic fields in high-mass stars.

O-type stars are unique laboratories for investigating the physics of stellar magnetism. Magnetic fields have clear influence on their rotation rates (rotation periods of most detected magnetic O stars are significantly longer than those of non-magnetic O stars of similar spectral types; e.g. Ud-Doula & Owocki 2002; Sundqvist et al. 2012). The lives of magnetic O-type stars are therefore expected to differ significantly from those of their non-magnetic brethren.

The lives of magnetic O stars of similar spectral types; e.g. Ud-Doula et al. 2009; Howarth et al. 2007; Martins et al. 2010). Evolutionary models (Maeder & Meynet 2003, 2004) and, recently, observations (Briquet et al., MNRAS, submitted) of massive stars suggest that the internal rotation profile is strongly modified by the presence of a magnetic field, enforcing essentially solid-body rotation through deformation of the star such that the magnetic field and the ofp characteristics.

The detection (e.g. Grunhut et al. 2009), empirical characterization of magnetic fields in high-mass stars. Magnetic fields have clear influence on their rotation rates (rotation periods of most detected magnetic O stars are significantly longer than those of non-magnetic O stars of similar spectral types; e.g. Ud-Doula & Owocki 2002; Sundqvist et al. 2012). The lives of magnetic O-type stars are therefore expected to differ significantly from those of their non-magnetic brethren.

The subject of the present paper, NGC 1624-4, is an Of?p star (Walborn 1972) to describe spectra of early O-type stars exhibiting the presence of C I lines. Well-studied Of?p stars are now known to exhibit periodic spectral variations (in Balmer, He i, C ii and Si ii lines), narrow P Cygni or emission components in the Balmer lines, and UV wind lines weaker than those of typical Of supergiants (see Naze et al. 2011 and references therein).

With our report of a detection of a magnetic field in NGC 1624-2, magnetic fields have now been firmly detected in all of the 5 known Galactic members of this class - HD 191612: Donati et al. (2006a, b), Wade et al. (2011); HD 108: Martins et al. (2010); HD 148937: Hubrig et al. (2008); Wade et al. (2010); CPD -28 2561: Hubrig et al. (2012); Wade et al. (2012b); NGC 1624-2: This paper - prompting the inference that there is a direct physical relationship between the magnetic field and the Of?p characteristics.

According to the recent analysis by Jose et al. (2011), NGC 1624 is a young open cluster located significantly above the Galactic plane. Their analysis yields a heliocentric distance of 6 ± 0.8 kpc (in agreement with that found in the pioneering study of Moffat et al. 1979) and an age of no greater then ~ 4 Myr. In addition to NGC 1624-2, which is by far the brightest cluster member, 3 other apparently bright optical sources are located within 2 arcmin of the cluster centre. These sources are reported to be an early B-type main sequence star, and two probable F giants (which are probably not physically associated with the cluster).

The current paper provides a first observational characterization of NGC 1624-2, the faintest of the known Galactic Of?p stars (V = 11.8). In particular we report the physical parameters of the star, its rotational period, the detection of its magnetic field, and a preliminary characterization of its magnetic and magnetospheric characteristics. In Sect. 2 we describe the spectroscopic and spectropolarimetric observations upon which we base our results. In Sect. 3 we provide a short overview of the spectral properties of the star. In Sect. 4 we derive the physical properties of the star and its wind. In Sect. 5 we determine the spectral variation period of the star. In Sect. 6 we describe the magnetic field diagnosis and our constraints on the surface magnetic field. In Sect. 7 we characterize its X-ray properties based on archival data. In Sect. 8 we describe the probable magnetospheric properties of the star. In Sect. 9 we discuss our results and summarize our conclusions.

2 OBSERVATIONS

2.1 Spectroscopic observations

The optical spectroscopic observations for the period determination were obtained within the context of three different projects. High resolution (R = 30 000) spectroscopy was obtained with the NoMaDS project (Maiz Apellániz et al. 2011) using the 9.2 m Hobby-Eberly Telescope (HET). Intermediate resolution (R = 2 500–4 000) spectroscopy was obtained within the GOSSS project (Maiz Apellániz et al. 2011) using the 1.5 m telescope of the Observatorio de Sierra Nevada (OSN), the 3.5 m telescope of the Calar Alto Observatory (CAHA), and the 4.2 m William Herschel Telescope at the Observatorio del Roque de los Muchachos (ORM), and the 2 m Himalayan Chandra Telescope at the Indian Astronomical Observatory (IAO).

Table 1. Log of spectroscopic observations used to determine the period. B refers to the spectral range that includes He i λ4471, He ii λ4542, He i λ4686, and Hβ; V to the range that includes He i λ5876; and R to the range that includes Hα. J stands for the low-resolution observations from Jose et al. (2011), G for the intermediate-resolution GOSSS observations (Maiz Apellániz et al. 2011), and N for the high-resolution NoMaDS observations (Maiz Apellániz et al. 2011).

| Date       | B | V | R | Date       | B | V | R |
|------------|---|---|---|------------|---|---|---|
| 2006-09-06 | J | J | J | 2011-11-13 | N | N | N |
| 2006-09-08 | J | J | J | 2011-11-17 | N | N | N |
| 2007-01-26 | J | J | J | 2011-11-18 | N |   |   |
| 2008-10-14 | G | G |   | 2011-11-19 | N |   |   |
| 2009-09-28 | G |   |   | 2012-01-15 | N | N | N |
| 2009-09-29 | G |   |   | 2012-01-20 | N | N | N |
| 2009-09-30 | G |   |   | 2012-01-22 | N | N | N |
| 2009-11-01 | G |   |   | 2012-01-24 | N | N | N |
| 2009-11-03 | G |   |   | 2012-01-27 | N | N | N |
| 2009-11-17 | J | J | J | 2012-02-11 | G | G | G |
| 2009-11-24 | G |   |   | 2012-02-15 | G | G | G |
| 2011-08-22 | N | N | N | 2012-03-04 | N | N | N |
| 2011-09-09 | G | G |   | 2012-03-12 | N | N | N |
| 2011-10-02 | N | N | N | 2012-03-22 | N | N | N |
| 2011-10-03 | N | N | N | Total N   | 7 | 13| 13|
| 2011-11-03 | N | N | N | Total G   | 9 | 3 | 7 |
| 2011-11-10 | N | N | N | Total J   | 4 | 4 | 4 |
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Figure 1. Two NoMaDS spectra of NGC 1624-2 (top, obtained on 22 Aug 2011, high state, phase 0.92; middle, obtained on 11 Nov 2011, low state, phase 0.43). The bottom spectrum represents the difference (high minus low). The spectra have been convolved to a resolving power $R = 10000$ for display purposes.

Figure 2. Of?p-diagnostic emission lines of C iii and N iii near maximum emission at the full ESPaDOnS resolving power ($R = 65000$). Note the remarkable composite emission profiles with broad and narrow components, not seen in previously investigated members of the Of?p category.

The 19 GOSSS spectra were obtained with various spectrographs fed by the OSN, CAHA and WHT telescopes as part of the larger Galactic O-Star Spectroscopic Survey. The data were reduced using a pipeline specifically written for the project, described by Sota et al. (2011).

A log of the 64 spectroscopic observations is presented in Table 1, where we specify which regions were observed on each date.

2.2 Spectropolarimetric observations

Five high resolving power ($R = 65000$) spectropolarimetric (Stokes I and V) observations of NGC 1624-2 were collected with ESPaDOnS at the Canada-France-Hawaii Telescope (CFHT) between Feb 1 and 9 2012. An additional observation was obtained with Narval (essentially a twin of ESPaDOnS) on the Bernard Lyot telescope (TBL) on Mar 24 2012. All of the spectropolarimetric observations were obtained within the context of the Magnetism in Massive Stars (MiMeS) Large Programs. Each spectropolarimetric sequence consisted of four individual subexposures, each of 600 s duration (for ESPaDOnS) or 1200 s duration (for Narval), taken in different configurations of the polarimeter retarders. From each set of four subexposures we derived Stokes I and Stokes V spectra following the double-ratio procedure described by Donati et al. (1997), ensuring in particular that all spurious signatures were removed to first order. Null polarization spectra (labeled N) were calculated by combining the four subexposures in such a way that polarization cancels out, allowing us to verify that no spurious signals are present in the data (see Donati et al. 1997, for more details on the definition of N). All frames were processed using the automated reduction package Libre ESpRIT (Donati et al. 1997). The peak SNRs per 2.6 km s$^{-1}$ velocity bin in the reduced spec-

http://hydra.as.utexas.edu/?a=help&h=29, ver. 22 Feb 2012
3 THE OPTICAL SPECTRUM OF NGC 1624-2

Fig. 1 shows the blue-green spectra of NGC 1624-2 from the HET/NoMaDS data (convolved with a Gaussian to a uniform $R = 10000$ for classification purposes) near maximum and minimum emission phases, together with their differences. The apparent spectral types from the He ionization ratios are O6.5 and O8, respectively, although both are affected by particular spectral features: at maximum, longward emission filling in He i $\lambda$4471 is clearly seen, while at minimum, the He i and He ii profiles are very different due to the stronger Stark wings in the latter, and indeed, the equivalent width ratio $\sim 1$ corresponds to a type near O7.

Fig. 2 displays the N iii $\lambda$4640, C iii $\lambda$4650 complex near maximum emission at the full ESPaDOnS resolving power of 65000. NGC 1624-2 exhibits the most extreme Of?p spectrum known to date, with the C iii emission lines stronger than those of N iii, and stellar Balmer emission much stronger than in any other. The N iii and C iii features (as well as, we suspect, He ii $\lambda$4686) display remarkable composite emission profiles with broad and narrow components, not seen in previously investigated members of the Of?p category. We hypothesize that the broad components are photospheric as in normal Of or Ofc stars (Walborn et al. 2010), while the narrow components typical of Of?p spectra are magnetospheric. In agreement with this interpretation, it is seen in Fig. 1 that only the narrow components vary with phase. However, the narrow C iii emission does not disappear at minimum, so unlike most other members of the category NGC 1624-2 remains Of?p at both extreme phases. Moreover, the apparently greater intensity of C iii as compared to N iii is largely due to the broad component, so that the intensities of both species in the narrow system are more comparable, similarly to other Of?p spectra.

This is the first case combining Ofc and Of?p emission profiles, for which we introduce the new notation Of?cp; thus the full classifications of these spectra are now O6.5f?cp and O8f?cp at maximum and minimum, respectively. As discussed by Walborn et al. (2010), the Ofc phenomenon in normal Galactic spectra is strongly peaked toward type O5. However, the optical component of the high-mass X-ray binary HD 153919 (2U 1700-37) is O6.5 Iafc (see, e.g., Conti & Cowley 1975, A. Sota et al. in prep.), as is the primary of the LMC double-lined spectroscopic binary R139 (Taylor et al. 2011). Thus, the Ofc phenomenon also occurs at later spectral types in some anomalous objects.

4 STELLAR PHYSICAL AND WIND PROPERTIES

The atmospheric parameters of NGC1624-2 have been derived by means of spectroscopic analysis with the code CMFGEN, fitting the minimum-emission state spectrum (the average of NoMaDS spectra acquired on 17/18 Nov 2011). A full description of CMFGEN is provided by Hillier & Miller (1998). In brief, it computes non-local thermodynamic equilibrium (non-LTE) atmosphere models with winds and line–blanketing. The statistical equilibrium and radiative transfer equations are solved in the comoving frame through an iterative scheme to compute the level populations and radiation field. The temperature structure is set by the condition of radiative equilibrium. Our models include the following elements; H, He, C, N, O, Ne, Si, S, Ar, Ca, Fe, Ni. The solar abundances of Grevesse et al. (2007) are used unless stated differently. The velocity structure is specified at the beginning of the computation. It
is usually a combination of a pre-computed photospheric structure connected smoothly to a so-called β velocity law ($v \propto (1 - r/R_\star)^\beta$ where $r$ is the radial coordinate and $R_\star$, the stellar radius). This structure is subsequently iterated to satisfy the momentum equilibrium equation in the inner atmosphere. Once the atmosphere model is converged, a formal solution of the radiative transfer equation is performed to yield the emergent spectrum. A microturbulent velocity varying with height from 10 to 200 km s$^{-1}$ (beginning in the photosphere and continuing to 100 $R_\odot$) is used.

Prior to a comparison between synthetic and observed spectra, it is necessary to determine the projected rotational velocity and macroturbulent broadening. We used the Fourier transform method for the former (e.g. Lankov 1993; Simón-Díaz et al. 2006), focusing on the C iv $λ\lambda 5801$ line. The Fourier transform did not show any zero before reaching the noise level, implying an upper limit on $v \sin i$ of ~15 km s$^{-1}$. Adapting this value, we convolved our synthetic spectra with a rotational profile and a Gaussian profile aimed at reproducing isotropic macroturbulence. We found that a macroturbulent velocity of about 25 km s$^{-1}$ gave the best fit to the observed He lines. We note based on the results of Sect. 4 that this additional broadening is likely to be magnetic in origin, and so isotropic macroturbulence will provide only an approximate reproduction of its effects. The combined line broadening (rotational, turbulent, magnetic) of NGC 1624-2 is comparable to that of the very sharp-lined magnetic O9IV star HD 57682 (Grunhut et al. 2009, and Grunhut et al., MNras, submitted).

The He i/He ii ionization balance was used to derive $T_\text{eff}$. As for the other O?P stars, we relied on the spectrum closest to the minimum-emission state. It has the least contaminated He i lines. Based on the absence of significant variability of the majority of the He ii lines in our spectra, we assume these lines are principally photospheric. Fig. 3 (left panel) shows the He lines (7 lines of He i, 3 lines of He ii; He ii $λ 4686$ was not used, as it is strongly variable) used in our analysis together with three selected models at 33 kK, 35 kK and 37 kK. Overall, the 35 kK model provides the best representation of the observed profile. The He ii lines are either too weak or too strong if $T_\text{eff}$ = 37 kK or 33 kK respectively. The He i lines also appear too strong at low $T_\text{eff}$. However, we note that the exact shape of the He i lines is uncertain (due to residual contamination by unmodelled contributions from the non-spherical component of the wind) and consequently, a safe uncertainty on $T_\text{eff}$ is 2000 to 3000 K.

The surface gravity of NGC 1624-2 was derived from the shape of the Balmer-line wings, as is usually done for O stars. We found that a value of $\log g = 4.0$ was the best compromise to reproduce all lines. A slightly higher value ($\log g = 4.2$) is indicated by Hβ and He II compared to Hγ. We can safely exclude any value below 3.7, the broadening being insufficient to reproduce the observed profiles in this case. We thus adopt a value of $\log g = 4.0 \pm 0.2$.

We also investigated the nitrogen content of NGC 1624-2 by means of its N ii lines (e.g. Martins et al. 2012). We used the N ii $λ 1240$, N ii $λ 4550-4525$ and N ii $λ 4535$ features, as all other nitrogen lines are either in emission, absent, or of very low S/NR (below 10). Assuming the adopted microturbulence described above, a value of $N/\text{H}= (1.0 \pm 0.4) \times 10^{-4}$ (by number) gives a satisfactory fit. Martins et al. (2012) tested the effect of a change of the microturbulent velocity in the atmosphere model computation (as well as the output synthetic spectrum) and found that a 5 km s$^{-1}$ increase in the microturbulence resulted in a 10-20% change in the derived abundance. This effect, while not negligible, is smaller than the effect of $T_\text{eff}$ uncertainties. Ultimately, while the exact value of the N abundance is uncertain due to the turbulent/magnetic and temperature uncertainties, we can conclude that the star is not strongly N enriched ($[\text{N/\text{H}}]<0.3$).

In the absence of UV spectroscopy, and given the peculiar shape of the emission in wind sensitive optical lines (He ii $λ 4686$, Hα), it is not possible to derive the mass loss rate of NGC 1624-2 based on the observations. First, the terminal velocity is not known (it is usually derived from the blueward extension of UV P-Cygni profiles). Secondly, the optical emission lines are very narrow, as
in the other O\textsc{ip} lines, and are probably the result of a complex (magnetically-confined) wind geometry that cannot be reproduced by our 1D models (Sundqvist et al. 2012).

In order to derive the distance and extinction of NGC 1624-2 we used the Bayesian (spectro)photometric code CHORIZOS (Maíz Apellániz 2004). In the latest CHORIZOS version, the user can select distance to be an independent parameter by applying atmosphere models (TLUSTY for OB stars; Lanz & Hubeny 2003, 2007) calibrated in luminosity with the help of Geneva stellar evolutionary tracks (excluding rotational effects). In such models the intrinsic parameters are effective temperature ($T_{\text{eff}}$) and photometric luminosity class (LC, defined in a similar way to its spectroscopic counterpart, with 0.0 corresponding to hypergiants and 5.5 to ZAMS). The extrinsic parameters are reddening ($E(B-V)$), extinction law ($R_V$), and logarithmic distance ($\log d$). CHORIZOS uses the family of extinction laws of Maíz Apellániz et al. (2012, in preparation), which improve upon the Cardelli et al. (1989) laws by using spline interpolation in the optical range instead of a seventh-degree polynomial and by correcting the extinction in the $U$ band.

As input photometry, we used the $UBVI$ magnitudes of Jose et al. (2011) and the $JHK$ magnitudes of 2MASS (Skrutskie et al. 2006). We discarded the $R$ magnitude of Jose et al. (2011) due to the influence of the H\alpha emission on the stellar SED, though we later checked that its inclusion would not have greatly changed our results. We did two different runs: in the first one, we fixed $T_{\text{eff}}$ to be 35 000 K (the value derived from spectroscopy) and allowed LC to vary in such a way that $3.7 < \log g < 4.3$ (slightly larger than the range derived from spectroscopy). In the second run, we left $T_{\text{eff}}$ as a free parameter and fixed LC to be 4.808 (i.e. close to the spectroscopic luminosity class $V$), since that value corresponds exactly to $\log g = 4.00$ (cgs) for $T_{\text{eff}} = 35 000$ K and $\log g$ is approximately constant for a fixed LC for O stars near LC = 5.0. In the two runs we left the three extrinsic parameters (reddening, extinction law, and logarithmic distances) free.

The results of the two CHORIZOS runs are shown in Table 2 and the mean SED from the first run is shown in Fig. 4. The two runs show good values of the reduced $\chi^2$, indicating that the photometry is consistent with the input SED models and extinction laws. All of the results are consistent (within 2$\sigma$) between the two runs, with the values for $E(4405 - 5495)$, $E(B-V)$, $R_V$, and $\log g$ practically indistinguishable. The most significant differences between the two runs are in $T_{\text{eff}}$, $\log L$, and $\log d$: the first run indicates a hotter, less luminous, and closer object in comparison with the second run. The second run has a better $\chi^2_{\text{red}}$ but that can be ascribed to a random fluctuation in the input photometry (the obtained $T_{\text{eff}}$ is within 2$\sigma$ of the spectroscopic value) or a small effect of the circumstellar material in the SED. The distance obtained in the first run ($5.2 \pm 1.1$ kpc) is in better agreement with the values from the literature ($\sim 6$ kpc). The values for the extinction indicate that $A_V$ is close to 3 magnitudes and that the value of $R_V$ is slightly larger than the mean Galactic value of 3.1-3.2, something that is typical for objects in H II regions.

Using the CHORIZOS-derived distance, reddening and extinction, the best CMFGEN fit to the SED corresponds to $\log L/L_\odot = 5.08$. With the quoted uncertainty on $d$, the uncertainty on $\log L/L_\odot$ is about 0.15 dex. Therefore the CMFGEN (5.08 ± 0.15) and CHORIZOS (5.13 ± 0.17) values of $\log L/L_\odot$ are in excellent agreement.

Based on the derived temperature ($T_{\text{eff}} = 35 000 \pm 2000$ K and luminosity (averaging the CMFGEN and CHORIZOS results, $\log L_\odot/L_\odot = 5.1 \pm 0.2$), we estimate the stellar radius $R_* = 10 \pm 3 R_\odot$. The mass of NGC 1624-2 derived from the spectroscopic analysis (i.e. from $\log g$ and the derived radius) is $M_* = 34 \pm 31 M_\odot$. The uncertainty is very large because the error on $\log g$ is nearly a factor of 1.6 (0.2 dex). This "spectroscopic" mass can be compared to the "evolutionary" mass derived simply from the ($T_{\text{eff}}, L_*$) position of NGC 1624-2 on the HR diagram. Using the evolutionary tracks of Meynet & Maeder (2005), we find $M_{\text{evol}} = 28 \pm 7 M_\odot$. This estimate implicitly assumes that the evolutionary tracks used can represent the evolution of the star. Given the peculiar properties of NGC 1624-2 (in particular its very strong magnetic field, very slow rotation and probably modified mass loss) this is not completely obvious, and thus the evolutionary mass should be regarded as only indicative.

The adopted parameters for NGC 1624-2 are summarized in Table 3.
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5 SPECTROSCOPIC VARIABILITY AND PERIOD

The first indication of variability in the spectrum of NGC 1624-2 resulted from a comparison of the different GOSSS observations obtained in 2008 and 2009 (see Table 4), reported by Walborn et al. (2010) and Sota et al. (2011). Indeed, Walborn et al. (2010) hinted at the possibility of variability on a time scale of days and suggested the need for further observations.

In order to determine the period of NGC 1624-2, we analyzed different optical lines and line ratios. We settled on four lines: Hα, He i λ5876, Hβ, and He ii λ4686; and one line ratio, He ii λ4542/He i λ4471. Of these six lines, three remain in emission in all of our observations (Hα, Hβ, and He ii λ4686), two remain in absorption (He ii λ4542 and He i λ4471) and the last one (He i λ5876) changes from emission to a complex absorption/emission profile. The variation of the He i λ5876 line is illustrated in Fig. 4.

We measured the emission equivalent width (EW; i.e. the integral of δλ×(flux-continuum)/continuum) of all the lines at every epoch and we analyzed the variations of the first four and the line ratio of the last two by means of Scargle periodograms as described by Horne & Baliunas (1986). We examined periods in the range 60-400 days, using 10\(^5\) periods uniformly distributed in log (period). In all five cases the periodograms show maxima between 156 and 159 days (Table 5). The periodogram for He ii λ4686 is shown in Fig. 5 (left panel). If we phase the EW measurements of this line with the adopted period (158 d, discussed below, and corresponding to the dominant peak of the periodogram), we obtained the variations shown in Fig. 5 (right panel), where phase 0 has been set for 9 Feb 2012 at noon UT (i.e. HJD 2455967.0; these same measurements are summarized in Table 4). The behaviour is the same for all the five quantities measured, with maxima (in either the EW or the line ratio) around phase 0.10-0.25 and minima around phases 0.6-0.75.

In addition, variations at the 0.01 magnitude level were detected in an R-band monitoring program of NGC 1624-2 with the 0.6 m telescope at the Esteve Duran Observatory that are consistent with the changes in EW(Hα) detected with spectroscopy.

To obtain a "best" period we tried two different approaches. First, we combined the five measured periods weighted with their uncertainties to obtain the sixth entry in Table 5."
The lack of any signature in the DIB feature. Note the co-addition of the 5 individual ESPaDOnS spectra. The final row provides the results for the Narval spectrum. The standard deviation for the measurements of each spectral line. The 7th row provides the longitudinal field measured from the mean spectrum obtained from the Interstellar Band (DIB) feature at 5797 Å.

(ii) times).

Table 6. Longitudinal field measurements obtained from individual lines in the ESPaDOnS and Narval spectra of NGC 1624-2, evaluated using Eq. (2). Uncertainties are formal errors computed by propagation of the spectral error bars. Listed are the heliocentric Julian date of the midpoint of the observation, the instrument used, the peak signal-to-noise ratio per 2.6 km s\(^{-1}\) velocity bin, and the evaluation of the longitudinal field from Stokes V. In no case is any detection obtained in the N profiles. The first 5 rows provide the results for the individual ESPaDOnS spectra. The 6th row provides the statistical mean and standard deviation for the measurements of each spectral line. The 7th row provides the longitudinal field measured from the mean spectrum obtained from the co-addition of the 5 individual ESPaDOnS spectra. The final row provides the results for the Narval spectrum.

| HJD     | Inst | SNR (bin\(^{-1}\)) | C iv λ5801 | C iv λ5811 | He i λ4712 | He i λ4921 | He i λ5015 | He ii λ5411 | He i λ7281 | O iv λ5591 |
|---------|------|-------------------|------------|------------|------------|------------|------------|------------|------------|------------|
| 958.715 | E    | 140               | 6.62 ± 1.4 | 8.27 ± 1.1 | 5.39 ± 1.0 | 7.46 ± 1.1 | 7.10 ± 1.3 | 3.50 ± 1.1 | 4.71 ± 0.7  | 8.91 ± 1.3  |
| 959.716 | E    | 135               | 8.94 ± 1.4 | 2.47 ± 1.0 | 3.21 ± 1.0 | 5.49 ± 1.2 | 5.19 ± 1.2 | 1.89 ± 1.3 | 4.34 ± 0.8  | 8.51 ± 1.5  |
| 960.713 | E    | 86                | 4.29 ± 1.7 | 5.58 ± 1.3 | 3.80 ± 1.6 | 9.70 ± 1.5 | 9.06 ± 1.5 | 1.68 ± 1.8 | 6.56 ± 0.9  | 7.28 ± 1.6  |
| 961.713 | E    | 137               | 5.65 ± 1.4 | 3.52 ± 1.0 | 2.95 ± 1.0 | 3.15 ± 1.1 | 8.08 ± 1.1 | 5.34 ± 1.2 | 2.76 ± 0.8  | 12.56 ± 1.4 |
| 966.720 | E    | 116               | 8.47 ± 1.6 | 4.06 ± 1.1 | 8.92 ± 1.3 | 7.84 ± 1.4 | 3.96 ± 1.3 | 5.85 ± 1.4 | 6.67 ± 0.9  | 1.63 ± 1.5  |
| Co-added| E    | -                 | 6.74 ± 1.9 | 4.77 ± 2.3 | 4.85 ± 2.5 | 6.73 ± 2.5 | 6.68 ± 2.1 | 3.65 ± 1.9 | 5.00 ± 1.6  | 7.78 ± 4.0  |
|          | E    | 300               | 6.59 ± 0.8 | 4.75 ± 0.6 | 4.66 ± 0.7 | 6.30 ± 0.6 | 6.89 ± 0.7 | 3.73 ± 0.6 | 4.73 ± 0.4  | 8.98 ± 1.0  |
| 1011.332| N    | 92                | 6.50 ± 1.6 | 7.66 ± 1.4 | 2.67 ± 1.4 | 5.78 ± 1.0 | 4.80 ± 1.7 | 5.51 ± 1.6 | 3.67 ± 1.0  | 0.80 ± 0.6  |

Table 5. Periods derived from analysis of spectra line EW variations. The procedures used are described in the text. The adopted period is that corresponding to “Combined 1”. The uncertainty quoted there is the dispersion of the five values, not the uncertainty of the mean. Even though the five values appear to be compatible amongst themselves (their normalized dispersion with respect to the weighted mean is 1.6), they are not fully independent measurements of the period, since the EWs and line ratios were not obtained at completely different times for the different quantities (e.g. Hβ, He i λ4686, and He ii λ4542 / He i λ4471 were obtained at exactly the same times).

We calculated the periodogram from the combined dataset, yielding the last entry in Table 5 (“Combined 2”). The uncertainty there is significantly worse than for the other five, which we attribute to the fact that the phased profile variations for the five measured quantities are not exactly the same.

We also checked that longer periods (e.g. twice the inferred period, i.e. 158 × 2 = 316 d, corresponding to a double-wave variation) were incompatible with the data (in that they generated no coherent variation). No other acceptable phasing is found at this period or any other period.

Therefore, our preferred period is the sixth entry in Table 5 which is 157.99±0.94 days, and we adopt the ephemeris of the spectroscopic variations as follows:

\[ JD = (2455967.0 \pm 10) + (157.99 \pm 0.94) \cdot E. \]  

According to this ephemeris, the ESPaDOnS spectropolarimetric observations were acquired at phases 0.95-1.0, while the Narval data were obtained at phase 0.28.

If we assume that the adopted variability period corresponds to the period of rotation of the star (as has been confirmed through the oblique rotator model for other O p stars: Wade et al. 2011, 2012), we tentatively conclude that NGC 1624-2 is a very slowly rotating star.
rotating star, with a rotational period nearly 0.5 years in duration, and a single-wave variation of the EWS of its emission and absorption lines. Such slow rotation would be consistent with the negligible rotational broadening of spectral lines reported in Sect. 4 and Sect. 6.

6 MAGNETIC FIELD

The individual reduced ESPaDOnS and Narval Stokes V spectra exhibit clear Zeeman signatures in profiles of various lines. Given the relatively low SNR (∼100–150) of the individual observations, this implies the presence of a very strong magnetic field.

Examination of the ESPaDOnS Stokes I spectra shows no significant variability of absorption or emission lines during the period of observation with that instrument (Feb 1–9 2012, phases 0.95–1.0 according to Eq. (1)). This is consistent with the long (158 d) period of spectral variability inferred for NGC 1624-2 (Sect. 5). Taking advantage of the stability of the spectrum, we co-added the 5 ESPaDOnS observations. Examples of Zeeman signatures present in the C iv λ5801, 5812, He i λ5876 and He i λ7065 lines of this mean spectrum are illustrated in Fig. 6. According to Eq. (1), the flux-weighted phase corresponding to the co-added ESPaDOnS spectrum is 0.96.

6.1 Longitudinal magnetic field from individual lines

We began by measuring the longitudinal magnetic field \( \langle B_z \rangle \) of individual spectral lines in each of the polarized spectra. We selected lines in absorption that appeared to be the least contaminated by emission and which showed clear Zeeman signatures in the co-added spectrum: C iv \( \lambda \lambda 5801, 5811, \) He i \( \lambda \lambda 4712, 4921, 5015, 7281, \) He ii \( \lambda \lambda 4541, 5591, \) and O iii \( \lambda 4363, 5593, 5015, 4959 \). We used the first-moment method of Rees & Semel (1979). All lines in the ESPaDOnS and Narval spectra are observed to have significant shifts from their rest wavelengths, corresponding to a radial velocity of about \( \pm 32 \) km s\(^{-1} \). We integrated the \( I/I_0 \) and \( V/I_0 \) profiles about their centres-of-gravity \( v_0 \) in velocity \( v \), in the manner implemented by Donati et al. (1997) and corrected by Wade et al. (2000):

\[
\langle B_z \rangle = \langle \frac{(v-v_0)V(v)}{I_0} \rangle = \frac{\int (v-v_0)V(v) \, dv}{\int [1-I(v)] \, dv}.
\]

In Eq. (2) \( V(v) \) and \( I(v) \) are the \( V/I_0 \) and \( I/I_0 \) profiles, respectively. The wavelength \( \lambda \) is expressed in nm and the longitudinal field \( \langle B_z \rangle \) is in gauss. The wavelength and Landé factor \( z \) correspond to those of each individual spectral line. Atomic data were obtained from the Vienna Atomic Line Database (VALD) where available. When experimental Landé factors were unavailable, they were calculated assuming L-S coupling. We integrated approximately symmetrical about \( v_0 \), using the observed span of the \( I \) and \( V \) profiles to establish the integration bounds. The \( \langle B_z \rangle \) measurements obtained from each of the lines in the individual spectra, and the co-added ESPaDOnS spectrum, are summarized in Table 6.

The mean obtained by averaging over all lines in Table 6 is 5.83 kG, with a standard deviation of 1.7 kG. This is consistent with the longitudinal field obtained from averaging the measurements from all lines in the individual ESPaDOnS spectra (5.78 kG with a standard deviation of 1.4 kG). The Narval spectrum yields a similar mean value of \( \langle B_z \rangle = 4.67 \) kG with a standard deviation of 2.2 kG. The longitudinal magnetic field of NGC 1624-2 is clearly remarkably strong.

Table 6 shows that most lines exhibit somewhat more scatter in their measurements than is predicted by the formal errors (i.e. the standard deviation in row 6 is frequently \( \times 2 \) times larger than the typical formal error of individual measurements). Examination of the measurements in greater detail revealed that the scatter results primarily from measurement of the first moment of \( V/I_0 \), i.e. the numerator of Eq. (2). To explore the origin of the scatter, we first inspected the Stokes V profiles of a given line, which we found to be identical within the noise. We then investigated the sensitivity of the measurements to adjustments of the integration range. We finally explored different methods of establishing \( v_0 \) (e.g. using only the Stokes V profile, using Stokes V weighted by the Stokes I line depth, fixing \( v_0 \) at a constant value). Ultimately, we concluded that the extra fluctuations are likely due to the difficulty of establishing the position of the centre-of-gravity \( v_0 \) in the relatively noisy profiles of the individual spectra. This is supported by the measurements from the higher SNR co-added spectra (i.e. row 7 of Table 6), which display no relatively extreme values, i.e. these values are in quite good agreement with the mean of the measurements for each line (row 6). We therefore conclude that measurements of \( \langle B_z \rangle \) from individual lines in the individual spectra are susceptible to relatively large fluctuations, while the averaged measurements (or measurements obtained from higher SNR co-added spectra) are more robust.

We also observe that some spectral lines yield significantly lower/higher values of the longitudinal field than the mean (e.g. He ii \( \lambda 4541 \) (3.73 \( \pm \) 0.6 kG in the co-added ESPaDOnS spectrum), vs. O iii \( \lambda 5591 \) (8.98 \( \pm \) 1.0 kG)). This may result from several effects. For example, most lines in the spectrum of NGC 1624-2 are variable. The origin of this variability is not understood in detail; it may be a result of changes in the formation environment of a particular spectral line, or varying contributions of the photosphere vs. the magnetosphere. If lines are affected differently by these (potentially various, potentially complex) contributions, this may modify the numerator of Eq. (2) (e.g. if the line forms in a region where the magnetic field may be intrinsically weaker, e.g. the circumstellar environment) or the denominator (e.g. if an absorption line is infilled by unpolarised emission). A thorough investigation of these effects will require good-quality observations spanning the rotational cycle of the star, coupled with a more sophisticated understanding of the line formation processes and the origin of the variability. This star is uniquely well-suited to such an investigation.

6.2 Longitudinal magnetic field from LSD profiles

We also analyzed the mean Stokes I and V profiles computed by means of Least-Squares Deconvolution (LSD; Donati et al. 1997). Donati’s implementation of LSD was applied to the individual and co-added Stokes spectra. We took advantage of the unique characteristics of NGC 1624-2 - the detectability of Zeeman signatures in many individual lines - to develop a custom line mask for this star. The mask includes 8 spectral lines (not surprisingly, the same 8 spectral lines analyzed above), and is summarized in Table 7.

Using the \( \chi^2 \) signal detection criteria described by Donati et al. (1997), we evaluated the significance of the signal in both LSD Stokes V and I. In no case is any signal detected in \( I \), while signal in \( V \) is detected definitely (false alarm probability \( fap < 10^{-5} \)) in all of our 5 ESPaDOnS observations, as...
Figure 7. LSD profiles of NGC 1624-2. Left: LSD profiles from the first mask corresponding to absorption lines. The weak absorption feature at $\sim -200$ km s$^{-1}$ is due to the DIB feature at 5797 Å. Right: LSD profiles of weak O$^{3+}$ emission lines. Note the inverted Stokes $V$ profile relative to the left panel. This phenomenon is discussed in Sect. 6.4.

Figure 8. Left - Splitting of the Stokes $I$ profiles of the C IV $\lambda\lambda 5801, 5812$ lines in the Narval spectrum. Overplotted are model profiles for a $\sim 20$ kG dipole viewed at the positive magnetic pole. A solar abundance of C is assumed, and no additional broadening has been added. Right - The same theoretical profiles are compared to the co-added ESPaDOnS spectrum. Note the weaker lines and absence of resolved splitting in the ESPaDOnS observation.

well as in the Narval observation. From each set of LSD profiles we measured the mean longitudinal magnetic field in both $V$ and $N$ using Eq. (2), integrating from -125 to +90 km s$^{-1}$ as determined from the radial velocity and extent of the Stokes $V$ and $I$ LSD profiles. We used the mean SNR-weighted Landé factor and wavelength, averaged over all lines in the mask. The longitudinal field measured from Stokes $V$ is detected significantly (i.e. $|z| = |B_z|/\sigma \geq 3$) in all but one of our observations, and in the mean ESPaDOnS spectrum at 10.7σ confidence ($\langle B_z \rangle = 5.35 \pm 0.5$ kG). The longitudinal field in the Narval spectrum, $5.07 \pm 1.2$ kG, is in formal agreement with the ESPaDOnS result obtained approximately 0.3 cycles earlier. In no case is the longitudinal field significantly detected in $N$. The results of the longitudinal field analysis are summarised in Table 8. The LSD Stokes $I$, $V$ and $N$ profiles extracted from the co-added ESPaDOnS spectrum are illustrated in Fig. 7 (left frame).

The longitudinal field inferred using LSD is formally consistent with that obtained from the individual line measurements from the co-added spectrum, using the standard deviation as the uncertainty. We note that the formal uncertainty associated with the LSD $\langle B_z \rangle$ measurement is substantially larger than the formal error we would compute from combining the co-added spectrum measurements (equal to 0.2 kG). This is a consequence of the inherent scaling applied to the LSD error bars in order to obtain a satisfactory agreement between the LSD polarized spectrum and the real observations (see e.g. Wade et al. 2000, Silvester et al. 2009). The LSD error bars therefore take into account line-to-line systematic errors such as those described in Sect. 6.1, and therefore probably provide a more realistic estimation of the uncertainties. As a consequence, we will adopt the LSD $\langle B_z \rangle$ measurements in the discussions that follow.

The strong longitudinal field inferred from the individual lines and LSD profiles fully supports our initial impression that the magnetic field of NGC 1624-2 is very strong. Assuming a limb darkening coefficient $u = 0.3$ and a centred dipolar magnetic field, such a strong longitudinal field implies a (minimum) polar surface field strength of the dipole of nearly 20 kG according to Eq. (1) of Preston (1967). Such a field is nearly 8 times stronger than that of any other known magnetic O-type star.
6.3 Zeeman splitting and magnetic field modulus

As discussed in Sect. 4, metallic spectral lines of NGC 1624-2 are very sharp. Given the strong magnetic field inferred above, a significant component of this broadening may result from the magnetic field. In fact, while examination of the Stokes I spectral lines in the ESPaDOnS spectra reveals no clear evidence of magnetic splitting, the C iv λ15801, 5812 lines in Narval spectra appear to show splitting in the line core (Fig. 8, left panel).

To characterize the magnetic properties of NGC 1624-2 in more detail, to infer the surface field modulus (i.e. the disc-integrated modulus of the magnetic field, to which the Stokes I Zeeman splitting is most straightforwardly related) and test the reality of the large longitudinal field discussed above, we attempted to reproduce the Stokes I and V profiles of C iv λ15801, 5811 using spectrum synthesis, taking into account the influence of the magnetic field. We used the Zeeman code (Lanstreet 1988, Wade et al. 2001), which computes profiles of spectral lines in LTE, taking into account Zeeman splitting and solving the equations of radiative transfer in all four Stokes parameters. We assumed a solar abundance ATLAS9 model atmosphere with $T_{\text{eff}} = 35$ kK and log $g = 4.0$. The assumption of LTE is probably rather poor in the Narval spectrum, we noticed that the bulk of the rotational and turbulent broadening assumed in Sect. 4 is likely magnetic. The Stokes V profiles predicted by the model are in agreement with the observed circular polarization, although the Narval observations are sufficiently noisy that this agreement lacks any real meaning. From this comparison we conclude that the Stokes I splitting observed in the Narval spectrum is consistent with the surface field expected from a nearly 20 kG magnetic dipole, and that in the presence of such a field other contributions to the broadening of the C iv lines (e.g. rotation, turbulence) are negligible (at least at the phase of the Narval observation).

Performing the same comparison with the co-added ESPaDOnS spectrum (Fig. 8, right panel) we see that the C iv lines are weaker than in the Narval spectrum, and that no splitting is obvious. We find that this can be achieved in the models by reducing the field modulus and adding a small additional broadening (rotational, turbulent or magnetic) to reproduce the wings of the line profile. This corresponds to a total equivalent broadening of about 30 km s$^{-1}$. We find that the largest field moduli corresponding to dipoles that we are able to accommodate in this manner are about 12 kG for λ5812, and 14 kG for λ5801. Thus it appears that the field modulus inferred from the ESPaDOnS spectrum (at phase 0.96) is at least slightly weaker (upper limit of 13 ± 1 kG) than that inferred from the Narval spectrum (14 ± 1 kG, at phase 0.28).

Table 7. Atomic data of lines used for magnetic analysis, including for construction of line masks used for Least-Squares Deconvolution.

| Wavelength (Å) | Species | $\chi_{\text{low}}$ (eV) | Landé factor |
|----------------|---------|------------------------|--------------|
| Absorption lines | | | |
| 4713.139 | He i | 20.964 | 1.250 |
| 4713.156 | He i | 20.964 | 1.750 |
| 4921.931 | He i | 21.218 | 1.000 |
| 5015.678 | He i | 20.616 | 1.200 |
| 5592.252 | O iii | 33.858 | 1.000 |
| 5801.312 | C iv | 37.549 | 1.167 |
| 5811.968 | C iv | 37.549 | 1.333 |
| 7281.349 | He i | 21.218 | 1.200 |
| Emission lines | | | |
| 7306.847 | O iii | 44.230 | 1.200 |
| 7307.117 | O iii | 44.243 | 1.750 |
| 7455.356 | O iii | 44.277 | 2.250 |
| 7515.987 | O iii | 44.277 | 2.250 |
| 8172.149 | O iii | 44.470 | 1.000 |

Table 8. Longitudinal field measurements of NGC 1624-2 obtained from LSD absorption line profiles. The final row provides the results for the mean spectrum obtained from coaddition of the 5 independent observations. In the "Inst" column, E=ESPaDOnS, N=Narval. In the "Det?" column, DD=Definite Detection.

| HJD -2455000 | Inst | SNR | Det? | LSD $B_l$ ($kG$) | LSD $N_l$ ($kG$) |
|--------------|------|-----|------|-----------------|-----------------|
| 958.715      | E    | 140 | DD   | 5.95 ± 1.0      | -1.61 ± 0.9     |
| 959.716      | E    | 135 | DD   | 6.33 ± 1.0      | -0.48 ± 1.0     |
| 960.713      | E    | 86  | DD   | 6.01 ± 1.8      | -1.30 ± 1.8     |
| 961.713      | E    | 137 | DD   | 4.76 ± 0.9      | -0.03 ± 1.0     |
| 966.720      | E    | 116 | DD   | 3.34 ± 1.3      | +2.25 ± 1.3     |
| Co-added ESPaDOnS | E     | 300 | DD   | 5.35 ± 0.5      | -0.33 ± 0.5     |
| 1011.332     | N    | 92  | DD   | 5.07 ± 1.2      | +1.37 ± 1.2     |

6.4 Inverted Stokes V profiles of weak emission lines

The Stokes I and V spectra of NGC 1624-2 are quite complex. For example, Fig. 8 shows 5 absorption/emission features of the three absorption features, one is unpolarised (the (interstellar) DIB), and two display Stokes V profiles consistent with a positive longitudinal field (i.e. with positive circularly-polarised flux in the blue wing). The two emission lines (He i λ8576 and He i λ7065) show Stokes V profiles similar to those of the absorption lines. However, because these lines are in emission (i.e. they have negative equivalent widths), the longitudinal field that would be inferred from these lines would in fact be negative.5

During our exploration of the Stokes V spectrum, we noticed that a number of weak emission lines of multiply-ionised light elements, primarily O iii, also exhibited Zeeman signatures. However, these signatures appeared to be inverted relative to those observed

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5 This complex behaviour underscores the value of high spectral resolving power for investigating magnetic fields of objects like NGC 1624-2.
in the absorption lines. We constructed a second LSD mask consisting only of those lines (see Table 7), and extracted the mean LSD profile. As shown in Fig. 7 (right panel), our initial suspicions were verified. These weak emission lines do exhibit inverted Stokes V signatures relative to the absorption lines and other strong emission lines such as He \( \text{i} \) 45876.

According to our CMFGEN models, these lines should form very close to the photosphere in normal O-type stars. In the spectrum of NGC 1624-2, the width and radial velocity of these lines are consistent with those derived from the C iv absorption lines, suggesting that this is probably true is the present case.

The reversed signatures in these lines can be naturally explained if the V profiles are formed in emission. This is in contrast to the other emission lines - "wind lines" - which exhibit V signatures with signs that are consistent with those of the absorption lines. We interpret this to indicate that these latter signatures do not form in emission (i.e. in the emitting region). Rather, they would form primarily in the photosphere in absorption lines (where the source function is decreasing with height). The emission contribution of the magnetosphere and wind - dominating the observed lines - would presumably form at relatively large distances from the star, where the dipole field has decreased significantly in strength, and would therefore contribute only weakly to the observed V profiles.

Measuring the longitudinal field from the O in LSD profiles yields \( B_\lambda = 2.58 \pm 0.7 \text{ kG} \). The longitudinal field from these emission lines is therefore consistent in sign with that measured from the absorption lines, but more than a factor of 2 smaller. However, as discussed above the emission lines are not predicted to probe substantially different spatial regions from the absorption lines, at least as estimated from a spherical wind model. An intriguing possibility that potentially explains the weaker longitudinal field strength discussed above the emission lines are not predicted to probe sub-absolute, some-what the spectrum is very hard, with only one count below 1 keV. This suggests either very hot plasma, or a highly absorbed, somewhat cooler plasma.

### Table 9. Single-temperature APEC plasma models, absorbed by a cool ISM model.

| \( N_{\text{ISM}} \) (10\(^7\) cm\(^{-2}\)) | \( N_{\text{local}} \) (10\(^7\) cm\(^{-2}\)) | \( kT \) (keV) | Abs. flux\(^a\) (10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\)) | \( L_X \) (10\(^3\) erg s\(^{-1}\)) |
|----------------|----------------|-------------|----------------|-------------|
| 0.48           | 0              | 2.3\(^{+0.9}_{-0.4}\) | 5.0\(^{+2.0}_{-1.0}\) | 2.4\(^{+2.0}_{-1.1}\) |
| 0.48           | 1.9\(^{+0.7}_{-0.5}\) | 0.7\(^{+0.3}_{-0.2}\) | 4.3\(^{+2.9}_{-1.2}\) | 1.8\(^{+1.8}_{-1.3}\) |

\(^a\) In the 0.5 - 7.0 keV band.

\(^b\) The absorbed flux was corrected for the \( N_{\text{ISM}} \) only.

We modelled the ACIS-I CCD spectrum in XSPEC 12.7 (Arnaud 1996) with a single-temperature, solar abundance (Asplund et al. 2005) APEC plasma (with \( \alpha \) = 2.0.1, Smith et al. 2001), and the cold ISM absorption model of Wilms et al. (2000). Given the low number of counts, we binned the spectrum from 0.5 to 7.0 keV in such a way as to obtain at least one count per bin (see Fig. 7). We therefore used the C-statistic to determine the best-fit model and place constraints on the model parameters. We used an ISM column density \( N_{\text{ISM}} = 0.48 \times 10^{22} \text{ cm}^{-2} \), determined from \( E(B-V) = 0.802 \) and \( R_v = 3.74 \). For such a low column density, the resulting best fit value for the plasma temperature is quite high (\( kT = 2.3^{+0.9}_{-0.3} \) keV), although the fit is rather poor.

We then allowed for the possibility of extra local absorption of the X-rays (from the wind or from a magnetosphere), in addition to the ISM column value of \( N_{\text{ISM}} = 0.48 \times 10^{22} \text{ cm}^{-2} \). The resulting fit, shown in Fig. 10 is marginally better. The temperature is lower – \( kT = 0.7^{+0.2}_{-0.1} \) keV – and the necessary extra column density would be surprisingly high \( N_{\text{local}} = 1.9^{+0.7}_{-0.5} \times 10^{22} \text{ cm}^{-2} \) compared to typical O-type stars (e.g. Nazé et al. 2011). Fig. 10 shows the C-statistic, 1, 2 and 3 \( \sigma \) contours for the plasma temperature and local absorbing column, to illustrate the possible range in parameters. Higher SNR data are therefore needed to robust constraints on the plasma temperature and absorbing column.

The absorbed fluxes for the two models described above range from 3-6\times10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}. Correcting for the ISM column density only and using a distance of 5.2 \pm 1.1 kpc, the X-ray luminosity is \( 1.4\times10^{32} \text{ erg s}^{-1} \). With a luminosity of \( \log(L_X/L_\odot) = 5.1 \), the X-ray efficiency is therefore \( \log(L_X/L_{\text{bol}}) \sim -6.4 \), a factor of about 4 higher than the canonical value for O stars of \( \sim 7 \) (Nazé et al. 2011).

High X-ray luminosity is a common feature among magnetic O-type stars with confined winds. The Of?p stars HD 108, HD 191612 and HD 148937, as well as O7V star \( \theta^1 \) Ori C, have \( \log(L_X/L_{\text{bol}}) \) from \( -6.0 \) to \( -6.2 \) (Chlebowski 1989; Nazé et al. 2004; Gagné et al. 2005; Nazé et al. 2007, 2008). However, these stars show a wide range of plasma temperatures. For the magnetic Of?p stars the plasma is dominated by a cool component similar to normal O-type stars, even if some hotter plasma is present. On the other hand, the X-rays of the O-type star \( \theta^1 \) Ori C are dominated by the hard component. At first glance, NGC 1624-2 seems to have hotter plasma than normal O-type stars. However, a full, detailed modelling of NGC1624-2 must await higher SNR X-ray observations.

\(^6\) Note that the local absorbing material may have different absorbing properties than assumed here (see for example Leutenegger et al. 2010).
NGC 1624-2: A slowly rotating, X-ray luminous Of?p star with an extraordinarily strong magnetic field

8 THE GIANT MAGNETOSPHERE OF NGC 1624-2

Magnetospheres of O and early B stars form through the channelling and confinement of an outflowing wind by the star’s magnetic field. This magnetic control breaks the symmetry of radiatively-driven winds, and therefore will influence observable wind diagnostics, such as Balmer line emission (Landstreet & Borra 1978) and wind resonance lines in the UV (Shore & Brown 1990). Furthermore, material forced to flow along the field lines will collide near the tops of closed loops, producing a shock-heated volume of plasma that will eventually cool, radiating X-rays (Babel & Montmerle 1997a,b). Given the large mass-loss rate expected for a 35 kK O-type star, and the observed strong magnetic field, it is highly probably that such a structure exists around NGC 1624-2.

As presented by ud-Doula & Owocki (2002), the global competition between the magnetic field and stellar wind can be characterized by the so-called wind magnetic confinement parameter

\[ \eta_w \equiv \frac{B_c^2 R_e^4}{M \kappa_{esc}} \]

which depends on the star’s equatorial surface field strength \( B_{eq} \), stellar radius \( R_\star \), and wind momentum \( M \kappa_{esc} \). For a dipolar field, one can identify an Alfvén radius \( R_A \equiv \eta_w^{1/3} R_\star \), representing the extent of strong magnetic confinement of the wind. Above \( R_A \), the wind dominates and stretches open all field lines. But below \( R_A \), the wind material is trapped by closed field line loops, and in the absence of significant stellar rotation is pulled by gravity back onto the star on a dynamical (free-fall) time-scale.

To estimate the wind momentum of NGC 1624-2, we determined the theoretical wind terminal velocity given by:

\[ v_\infty = 2.6 \sqrt{\frac{GM(1 - \Gamma_\star)}{R_\star}} \]  

(Lamers et al. 1993) where \( \Gamma_\star \equiv \kappa L/4\pi GMc \) is the standard Eddington parameter for electron scattering opacity in a fully ionized wind \( \kappa_e = 0.34 \text{ cm}^2 \text{ g}^{-1} \). Using the adopted parameters given in Table 2, we obtain \( v_\infty = 2875 \text{ km s}^{-1} \). We used the mass-loss rate recipe of Vink et al. (2000, 2001) and we obtain \( M = 1.6 \times 10^{-7} M_\odot \text{ yr}^{-1} \), roughly consistent with the other Of?p stars. Using a dipolar field strength of 20 kG \( B_c \), this leads to a magnetic confinement \( \eta_w \simeq 1.5 \times 10^4 \). The closed loop region of the magnetosphere therefore extends up to \( R_M \simeq 11 \pm 4 R_\star \) (assuming a conservative 40% uncertainty in \( B_c \) and a factor of two uncertainty in wind momentum). Therefore, even taking into account the uncertainties, the magnetosphere of NGC 1624-2 is intrinsically large, and substantially larger than that of any other magnetic O-type star (for all of which \( R_A < 4 R_\star \)).

In the presence of significant stellar rotation, centrifugal forces can support any trapped material above a Kepler co-rotation radius \( R_{Kep} \equiv (GM/\omega^2)^{1/3} \). This requires that the magnetic confinement extend beyond this Kepler radius, in which case material can accumulate to form a centrifugal magnetosphere (e.g. Townsend et al. 2008). In the case of NGC 1624-2, the slow rotational period puts the Kepler radius much farther out (40 \( R_\star \)) and no long-term accumulation of wind plasma is possible. However, the transient suspension of circumstellar material still results in a global over-density in the closed loops. For O-type stars with sufficient mass-loss rates, the resulting dynamical magnetosphere can therefore exhibit strong emission in Balmer recombination lines (Petit et al. 2011, Sundqvist et al. 2012). For the huge volume of the magnetosphere of NGC 1624-2, we would expect particularly strong Balmer emission. In fact, as illustrated in Fig. 2 of Walborn et al. (2010) and Fig. 11 NGC 1624 has - by a large margin - the strongest Balmer emission of all known magnetic O-type stars.

In the prototypical magnetic O-star \( \theta^1 \) Ori C, the hard and luminous X-rays are seen to be rotationally modulated (Gagné et al. 1997, Gagné et al. 2008) used 2D magnetohydrodynamical (MHD) simulations to show that the high temperature plasma can be well explained by shocks extending up to 1.5 \( R_\star \), comparable to its inferred Alfvén radius of 2 \( R_\star \). Therefore, the trapped wind has only been accelerated to a fraction of its potential terminal velocity before reaching the top of the closed loops.

In a larger magnetosphere such as NGC 1624-2, the wind speed could in principle get higher before crossing the shock front.

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While the maximum measured field modulus is \( 14 \pm 1 \text{ kG} \), to remain consistent with \( \eta_w \) inferred for other magnetic O stars we employ for this purpose the equatorial field of a dipole of polar strength 20 kG inferred from the longitudinal field.
and one could expect harder X-ray emission than in other magnetic O-type stars. Furthermore, if a larger fraction of the wind gets shock-heated, the overall emission level could be higher. However, the current X-ray observations do not provide sufficient constraints on the plasma temperature distribution, the total X-ray flux and the column density to be meaningfully modelled with sophisticated magnetosphere models.

9 DISCUSSION AND CONCLUSION

We have discovered an extraordinarily strong magnetic field (maximum mean longitudinal magnetic field \( B_{\text{r}} = 5.35 \pm 0.5 \text{ kG} \), corresponding to a dipole of surface polar strength \( \sim 20 \text{ kG} \)) in the Of?p star NGC 1624-2 that distinguishes it qualitatively from other known magnetic O-type stars. Of particular interest is the presence of clear Zeeman signatures in individual spectral lines, and the apparent detection of resolved Zeeman splitting (corresponding to a maximum mean magnetic field modulus of \( B = 14 \pm 1 \text{ kG} \)). The detectability of Zeeman splitting should in principle allow a much stronger constraint on the geometry and topology of the star’s magnetic field as compared to any other magnetic O-type star, once additional observations are acquired. We also suggest that NGC 1624-2 rotates very slowly, spinning once in approximately one-half year. Such a conclusion is in good agreement with the negligible \( v \sin i \) inferred from modelling the magnetically-split line profiles. It has been established that all known magnetic O-type stars have diverse but relatively long periods of rotation, from about a week (HD 148937: Nazé et al. 2008) to perhaps more than 50 years (HD 108: Nazé et al. 2001).

The most common mechanism invoked to produce such slow rotation is magnetic braking, i.e. the shedding of rotational angular momentum via the stellar wind and enhanced lever arm provided by the magnetic field. If we employ the braking model described by Ud-Doula et al. (2009) (Eq. 25 of that paper), we can roughly compute the braking timescale \( \tau_{\text{spin}} \) as a function of the magnetic field strength, stellar mass and radius, mass loss rate and terminal velocity. Using the physical parameters reported in Table 1 and moment of inertia coefficient \( k \sim 0.1 \) (Claret 2004), we obtain a spin-down time for NGC 1624-2 of 0.24 Myr. As discussed in Sect. 1, the estimated maximum age of the cluster NGC 1624 is no greater than 4 Myr, i.e. no more than \( \sim 17 \tau_{\text{spin}} \). Such an age is, however, easily sufficient for the star to have undergone a slow initial rotation period to its current very long period. (For example, if we assume the star was initially rotating at critical \( P_{\text{crit}} = 1.1 \text{ d} \), the time required to slow the rotation to 158 \( \text{d} \) would be \( \ln(158/1.1) = 4.96 \tau_{\text{spin}} = 1.2 \text{ Myr} \)). On the other hand, if the cluster age is significantly younger than 4 Myr this would place constraints on the initial rotational speed of the star (requiring a slower initial rotation) or a reconsideration of the origin of the current slow rotation. These conclusions are subject to the assumptions and limitations of the braking model (e.g. aligned magnetic and rotation axes computed in 2D) and the uncertainties of the input parameters \( (B_0, M_\ast, R_\ast, M_\ast, v_\infty \) and \( k \)).

Indeed, the spectrum of NGC 1624-2 exhibits a number of peculiarities that distinguish this star from other Of?p stars. First, we have observed unprecedented composite profiles of the C iv \( \lambda 5801 \), 5811 lines with narrow and broad components. We hypothesize that the broad components are photospheric as in normal Of or Ofc stars (Walborn et al. 2010), while the narrow components typical of Of?p spectra are magnetospheric. Consistent with this interpretation, we observe that only the narrow components appear to vary with phase. Moreover, the narrow C iv emission does not disappear at minimum, so unlike most other members of this class, NGC 1624-2 remains Of?p at both extreme phases. We have also found that the absorption lines of NGC 1624-2 are very narrow, and that the widths of C iv \( \lambda 5801, 5811 \) can be reproduced essentially by magnetic broadening. This is in stark contrast to other Of?p stars for which the profiles of these lines are clearly dominated by turbulent broadening at the level of several \( 10^3 \text{ km} \text{s}^{-1} \). The origin of this difference is currently unknown.

We have also used the strong variations of various spectral absorption and emission lines to infer a unique and unambiguous spectral variation period of 157.99 ± 0.94 d. Based on the observed behaviour of all other known magnetic O-type stars, it is reasonable to assume this to be the stellar rotation period (an assumption that will be tested by acquisition of additional magnetic field measurements). This implies that NGC 1624-2 rotates very slowly, spinning once in approximately one-half year. Such a conclusion is in good agreement with the negligible \( v \sin i \) inferred from modelling the magnetically-split line profiles. It has been established that all known magnetic O-type stars have diverse but relatively long periods of rotation, from about a week (HD 148937: Nazé et al. 2008) to perhaps more than 50 years (HD 108: Nazé et al. 2001).

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In our analysis of the optical spectrum of NGC 1624-2, we derived a upper limit on the photospheric N abundance: \( [\text{N/H}] < 0.3 \). We consider this upper limit to be uncertain due to our present inability to directly include the influence of the strong magnetic field on the line formation in our NLTE spectrum synthesis model. Accurate knowledge of the surface N abundance represents an important constraint on the interior rotation profile of a magnetic early-type star. As reported by Meynet et al. (2011), when magnetic brak-
ing occurs in a massive star characterized by internal differential rotation, a strong and rapid mixing occurs in layers near the surface. This results in enhanced mixing, resulting in enriched surface abundances of nitrogen relative to similar models with no magnetic braking. However, when solid-body rotation is imposed in the interior, the star is slowed so rapidly that surface enrichments are in fact smaller than in similar models with no magnetic braking. Therefore magnetic braking can enhance the surface N abundance or, in contrast, have little effect on it, depending on the internal rotation profile of the star. Martins et al. (2012) investigated the N surface enrichment of 6 known magnetic O-type stars, including 3 Of?p stars. Depending on the assumed initial rotation velocity of the Of?p stars, they found that that they display surface nitrogen enrichments consistent with those of non-magnetic O stars (if their rotation was initially rapid, $v_{\text{rot}} \sim 300$ km s$^{-1}$), or enhanced relative to no-magnetic O stars (if their rotation was initially modest, $v_{\text{rot}} \sim$ a few tens $10$ km s$^{-1}$). Assuming NGC 1624-2 has a main sequence age no greater than 4 Myr, comparison of our preliminary N abundance with the figures presented by Martins et al. (2012) indicates that (1) NGC 1624-2 has a N abundance slightly lower than non-magnetic O stars with similar positions on the HR diagram; (2) that the abundance is low relative to that expected for a star of this age and mass if it was rotating initially at high velocity; (3) but consistent with the expected abundance if the star was rotating initially at lower velocity. However, as discussed above these results are quite tentative, and require more detailed modelling and a more robust determination of the age of the star before firm conclusions can be drawn.

As a consequence of its intense magnetic field, NGC 1624-2 is expected to host a magnetostreric sphere substantially larger than any other magnetic O-type star. The inferred magnetic wind confinement parameter, $\eta = 1.5 \times 10^4$, is 300 times larger than that of the Of?p star with the next-strongest field, HD 191612. This leads to a predicted Alfvén radius of $11.4 R_\ast$ (versus $2.2 R_\ast$ in the case of HD 191612). This much larger volume of confined plasma should result in much stronger magnetostric emission (e.g. according to the mechanisms discussed by Sundqvist et al. 2012). Indeed, the Hα emission of NGC 1624-2 is found to be substantially stronger than that observed in any other magnetic O-type star. For comparison, and as illustrated in Fig. 11 the maximum EW of Hα in the spectrum of HD 191612 is about 4 Å (e.g. Wade et al. 2011), while that of $\theta^1$ Ori C is about 2 Å (Stahl et al. 2008). The peak EW of the Hα line of NGC 1624-2 is 26 Å, 6.5 times greater than that of HD 191612 and 13 times greater than that of $\theta^1$ Ori C. Modeling of this remarkable Hα emission is an urgent priority, and first attempts are underway by Sundqvist, ud Doula et al. (priv. comm.).

It is expected that such strong magnetic wind confinement in the presence of such a powerful wind should lead to intense X-ray emitting shocks. Analysis of archival Chandra ACIS-I X-ray observations indicates a hard and luminous X-ray spectrum ($\log(L_x/L_{bol}) \sim -6.4$), qualitatively consistent with theoretical expectations as well as the behaviour of $\theta^1$ Ori C. However, the current observations are more or less equally consistent with a relatively hard, weakly extinguished source, or a relatively soft, highly extinguished source. New higher-quality X-ray observations will be required to draw useful quantitative conclusions about the X-ray properties of NGC 1624-2.

Due to the paucity of magnetic data, the magnetic topology and geometry of NGC 1624-2 are at present only weakly constrained. Although the geometry (i.e. the inclination angle $i$ and the magnetic obliquity $\beta$) is normally inferred from the variation of the longitudinal magnetic field, observations of other magnetic O stars (e.g. $\theta^1$ Ori C, HD 191612, HD 57682) show that a clear relationship exists between the EW variations of optical emission lines diagnostic of the wind (e.g. Hα, He i à5876, He ii à4686) and the longitudinal field variation. In particular, the emission extrema of these stars all correspond to extrema of the (sinusoidally-varying) longitudinal field, with the emission maximum corresponding to the maximum unsigned longitudinal field. If we assume that the magnetic topology of NGC 1624-2 is roughly dipolar, we can expect with reasonable confidence that the ESPaDOnS observation, acquired at phase 0.96 near emission maximum, corresponds to the approximate maximum of the longitudinal field. The longitudinal field measured from the Narval observation, acquired at phase 0.28, is not very different from that of the ESPaDOnS measurement, suggesting that the variation of the longitudinal field is not very large, and moreover that it does not change sign as the star rotates. This implies that we view essentially only one magnetic hemisphere during the rotation of the star, and consequently $i + \beta < 90^\circ$. This conclusion is supported by the single-wave nature of the EW variations. When both magnetic hemispheres are visible during the stellar rotation (i.e. $i + \beta > 90^\circ$, as in the case of HD 57682; Grunhut et al. 2009, and MNRRAS, submitted), the EW variations of the emission lines exhibit a double-wave variation. In contrast, smaller values of the sum $i + \beta$ produce single-wave variations (e.g. $\theta^1$ Ori C, HD 191612; Stahl et al. 2008; Howarth et al. 2007).

Clearly, NGC 1624-2 holds a special place amongst the known magnetic O-type stars. Its extreme magnetic field and puzzling spectral peculiarities have much to teach us, and demand immediate attention. Plans for observational follow-up - including optical spectroscopy, spectropolarimetry, and photometry; UV spectroscopy; and X-ray spectroscopy - are already underway, as are theoretical investigations of its Hα and X-ray properties to better understand the magnetospheric geometry, structure and energetics.

ACKNOWLEDGMENTS

GAW and AFJM acknowledge support from the Natural Science and Engineering Research Council of Canada (NSERC). JMA acknowledges support from [a] the Spanish Ministerio de Ciencia e Innovación through grants AYA2010-15081 and AYA2010-17631; [b] the Junta de Andalucía grant P08-TIC-4075; and [c] the George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy. YN acknowledges support from the Fonds National de la Recherche Scientifique (Belgium), the Communauté Francaise de Belgique, the PRODEX XMM and Integral contracts, and the ‘Action de Recherche Concertée’ (CFWBAcadémie Wallonie Europe). VP acknowledges support from the Fonds Québécois de la Recherche sur la Nature et les Technologies. STScI is operated by AURA, Inc., under NASA contract NAS5-26555. CFHT and TBL observations were acquired thanks for generous allocations of observing time within the context of the MiMeS Large Programs.

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