First detection of a magnetic field in the fast rotating runaway Oe star ζ Ophiuchi[*]

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The star ζ Ophiuchi is one of the brightest massive stars in the northern hemisphere and was intensively studied in various wavelength domains. The currently available observational material suggests that certain observed phenomena are related to the presence of a magnetic field. We acquired spectropolarimetric observations of ζ Oph with FORS 1 mounted on the 8-m Kueyen telescope of the VLT to investigate if a magnetic field is indeed present in this star. Using all available absorption lines, we detect a mean longitudinal magnetic field $\langle B_z \rangle_{\mathrm{all}} = 141 \pm 45$ G, confirming the magnetic nature of this star. We review the X-ray properties of ζ Oph with the aim to understand whether the X-ray emission of ζ Oph is dominated by magnetic or by wind instability processes.

1 Introduction

During the last years a gradually increasing number of O, early B-type, and WR stars have been investigated for magnetic fields, and as a result, about a dozen magnetic O-type stars are presently known (e.g., Hubrig et al. 2008; Martins et al. 2010; Hubrig et al. 2011a). The recent detections of magnetic fields in massive stars generate a strong motivation to study the correlations between evolutionary state, rotation velocity, and surface composition, and to understand the origin and the role of magnetic fields in massive stars.

The star ζ Ophiuchi (=HD 149757) of spectral type O9.5V is a well-known rapidly rotating runaway star with extremely interesting characteristics. It undergoes episodic mass loss seen as emission in Hα, and it is possible that it rotates with almost break-up velocity with $v \sin i = 400 \, \mathrm{km \, s^{-1}}$ (Kambe et al. 1993). Various studies indicate different types of spectral and photometric variability. The UV resonance lines show multiple discrete absorption components (DAC) in the UV (e.g. Howarth et al. 1984) and strong line profile variations in optical spectra reconciled with traveling sectorial modes of high degree (e.g. Reid et al. 1993). Highly precise *MOST* (Microvariability and Oscillations of Stars) satellite photometry in 2004 has yielded at least a dozen significant oscillation frequencies between 1 and 10 cycles/day, hinting at a behaviour similar to β Cephei-type stars (Walker et al. 2005). No unambiguous rotation period could be identified in spectroscopic and pho-

tometric observations, although Balona & Kambe (1999) favored a period in the region of 1 cycle/day.

ζ Oph is also well-known for its variability in the X-ray band. Oskinova et al. (2001) studied the *ASCA* observations of ζ Oph that covered just more than the expected rotation period of the star. A clearly detected periodic X-ray flux variability with ∼20% amplitude in the *ASCA* passband (0.5-10 keV) was reported. A period of 0.77 d was detected and a possible connection with the recurrence time (0.875 d±0.167 d) of the DACs in UV spectra of the star was discussed. The DACs in the spectra of O stars are commonly explained by large-scale structures in the stellar wind, modulated by rotation and possibly related to a surface magnetic field (Cranmer & Owocki 1996). Waldron et al. (in preparation, private communication) found that *SUZAKU* data on ζ Oph suggest a period of ∼0.98 d that is consistent but slightly larger than the X-ray periodicities found in *ASCA* data (Oskinova et al. 2001) and in *Chandra* HETGS data (Waldron 2005). In addition, the HETGS data appear to indicate an additional cyclic period of ∼0.33 d in the hard X-ray band (>1.2 keV).

The results of our previous studies seem to indicate that the presence of a magnetic field is more frequently detected in candidate runaway stars than in stars belonging to clusters or associations (Hubrig et al. 2011b; Hubrig et al. 2011a). The currently best available astrometric, spectroscopic, and photometric data were used to calculate the kinematical status of magnetic O-type stars with previously unknown space velocities. The results suggest that most of the magnetic O-type stars can be considered as candidate runaway stars.

The available observational material suggests that ζ Oph is a main sequence single star in the field with runaway characteristics. Usually, to explain the origin of massive stars in the field, two mechanisms are discussed in the literature. In one scenario, close multibody interactions in a dense cluster cause one or more stars to be scattered out of the region (e.g. Leonard & Duncan 1990). For this mechanism, runaways are ejected in dynamical three- or four-body interactions. An alternative mechanism involves a supernova (SN) explosion within a close binary, ejecting the secondary due to the conservation of momentum (Zwicky 1957; Blaauw 1961). Blaauw (1952) suggested the origin of ζ Oph in the Scorpius OB2 association due to its proper motion vector, which points away from the association. More recently, Hoogerwerf et al. (2001) suggested that the star gained it space velocity of $\sim 30 \, \text{km s}^{-1}$ in a supernova explosion within a close binary in Upper Scorpius about 1–2 Myr ago. The authors identified PSR B1929+10 as an associated pulsar with a characteristic age of $\sim$3 Myr, consistent with the kinematic age of ζ Oph within the uncertainties. Tetzlaff et al. (2010) reinvestigated the scenario of a binary SN in Upper Scorpius involving ζ Oph and PSR B1929+10 and concluded that it is very likely that both objects were ejected during the same supernova event. In their work, the considered association age range implies that the progenitor star of the produced neutron star had a spectral type between O6/O7 and O9 with a mass range from 18 to 37 $M_\odot$. The X-ray emission of the pulsar seems to be dominated by non-thermal radiation processes (e.g. Becker et al. 2006). An arc-like nebula surrounding PSR B1929+10 and extending up to $10''$ was identified in *Chandra* data and interpreted as a bow-shock nebula (Hui & Becker 2008). The estimated magnetic field strength in the shocked region accounts for $\sim 75 \, \mu$G, while the typical magnetic field strength in the ISM is about 2–6 μG.

The presence of a bow-shock nebula has also been detected for ζ Oph. Figure 1 shows an image based on archival *Spitzer* IRAC maps (AOR 17774848). Recently, Kobulnicky et al. (2010) analyzed a sample of bow shocks around massive stars in Cygnus-X. They used the analytical description of momentum-driven bow shocks and dust/polycyclic aromatic hydrocarbon emission models to estimate stellar mass loss rates from the observed properties of the bow shocks. It was found that mass-loss rates in the range between $10^{-7} M_\odot \, \text{yr}^{-1}$ and a few times $10^{-6} M_\odot \, \text{yr}^{-1}$ are required to generate the bow shocks around typical B2V - O5V type stars.

The mass-loss rate $\dot{M}$ of this star was empirically obtained from different diagnostics by a number of authors. Repolust et al. (2004) fitted the Hα photospheric absorption line and derived the upper limit on the ζ Oph mass-loss rate as $1.8 \times 10^{-7} M_\odot \, \text{yr}^{-1}$. Fullerton et al. (2006) determined the radio-based mass-loss rate of ζ Oph as $1.1 \times 10^{-7} M_\odot \, \text{yr}^{-1}$. The mass-loss rates determined from radio depend on the square of the density since the physical mechanism responsible for the radio emission is free-free
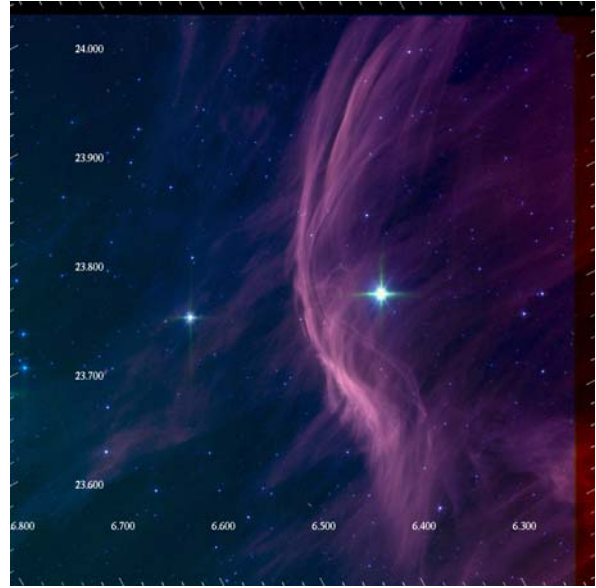

Fig. 1 (online colour at: www.an-journal.org) Combined IR *Spitzer* IRAC (3.6 μm blue, 4.5 μm green, 8.0 μm red) image of the bow shock around the runaway star ζ Oph. Archival data have been used. Galactic coordinates are shown. The image size is $\sim 36' \times 31'$.

emission. On the other hand, Fullerton et al. derive a much smaller mass-loss rate from fitting the UV P V resonance doublet, the product of the mass-loss rate and the ion fraction of P^{+4} being only $\dot{M}q(P^{+4}) \lesssim 1.3 \times 10^{-10} M_\odot \, \text{yr}^{-1}$ with $q(P^{+4}) \lesssim 1$. The mass-loss rates derived from fitting the wind profiles of UV resonance lines depend linearly on the density. To resolve this discordance in mass-loss determinations based on ρ^2- and ρ-diagnostics, Fullerton et al. suggest that the winds are strongly clumped with a volume filling factor of $\sim 10^{-3} – 10^{-5}$. Marcolino et al. (2009) analyzed optical and UV spectra of ζ Oph among their sample of O-type dwarfs. They derive an upper limit on the mass-loss rate of ζ Oph as $1.6 \times 10^{-9} M_\odot \, \text{yr}^{-1}$ if the wind was smooth. This value agrees with the $\dot{M}q(P^{+4})$ value obtained by Fullerton et al. (2006).

Using the example of the O-type supergiant ζ Puppis, Oskinova et al. (2007) demonstrated that the discordance of mass-loss rates found by Fullerton et al. can be overcome by accounting for stellar wind porosity (see also Sundqvist et al. 2010). It was found for the O5Ia star ζ Puppis that only a moderate reduction of the mass-loss rate by a factor of 2–3 (compared to the smooth wind models) is required to reproduce both Hα and P V lines. If this result holds also for non-supergiant O type stars, the mass-loss rate of ζ Oph is only a few times lower compared to the radio-based mass-loss determined by Fullerton et al., i.e. $\sim 10^{-7} M_\odot \, \text{yr}^{-1}$. Importantly, this mass-loss rate is in agreement with values that are required to produce bow shocks around O stars (Kobulnicky et al. 2010).

An additional aspect, which may hint at the presence of a magnetic field in runaway stars, is that a number of

individual abundance studies indicate nitrogen enrichment in the atmospheres of runaway stars (e.g. Boyajian et al. 2005). Nitrogen enrichment was found in ζ Oph by Villamariz & Herrero (2005). Recent NLTE abundance analyses (e.g., Morel et al. 2008; Hunter et al. 2008) suggest that slow rotators have peculiar chemical enrichment such as nitrogen excess or boron depletion, and these peculiarities are linked to the presence of a magnetic field. On the other hand, Hubrig et al. (2011c) showed that some magnetic massive stars previously assumed to be slow rotators, are in fact fast rotators, but are viewed close to their rotation poles.

To test the magnetic nature of this particularly interesting rapidly rotating runaway star, we acquired spectropolarimetric observations with the low-resolution spectropolarimeter FORS 1 at the VLT. In this work we report the first detection of a magnetic field in this star.

2 Magnetic field measurements

Spectropolarimetric observations with FORS 1 (Appenzeller et al. 1998) were obtained on 2008 May 23 (MJD 54609.34) using grism 600B and a slit width of 0.″4 to achieve a spectral resolving power of $R \approx 2000$. The use of the mosaic detector made of blue optimized E2V chips and a pixel size of 15 μm allowed us to cover a large spectral range, from 3250 to 6215 Å, which includes all hydrogen Balmer lines from Hβ to the Balmer jump. Six continuous series of two exposures with durations between 0.3 and 3 sec were taken at two retarder waveplate setups ($\alpha = +45°$ and $-45°$). For all but the first exposure pairs we achieved a signal-to-noise ratio between 1000 and 1500. More details on the observing technique with FORS 1 can be found elsewhere (e.g., Hubrig et al. 2004a, 2004b, and references therein). The mean longitudinal magnetic field, $\langle B_z \rangle$, was derived using

$$\frac{V}{I} = -\frac{g_{\text{eff}} e \lambda^2}{4 \pi m_e c^2} \frac{1}{I} \frac{dI}{d\lambda} \langle B_z \rangle , \qquad (1)$$

where V is the Stokes parameter that measures the circular polarisation, I is the intensity in the unpolarised spectrum, g_{eff} is the effective Landé factor, e is the electron charge, λ is the wavelength, m_e the electron mass, c the speed of light, $dI/d\lambda$ is the derivative of Stokes I, and $\langle B_z \rangle$ is the mean longitudinal magnetic field. The longitudinal magnetic field was measured in two ways: using only the absorption hydrogen Balmer lines or using the entire spectrum including all available absorption lines. We obtain for the mean longitudinal magnetic field using all available absorption lines $\langle B_z \rangle_{\text{all}} = 141 \pm 45$ G and for the mean longitudinal magnetic field using the hydrogen Balmer lines $\langle B_z \rangle_{\text{hyd}} = 123 \pm 54$ G. Our detection using the entire spectrum has a significance of 3.1σ, determined from the formal uncertainties we derive. In the Stokes V spectra distinct Zeeman signatures are well visible at the position of hydrogen and metal lines. In Fig. 2 we display Stokes I and V spectra in the spectral regions around Hβ and the Na I doublet.
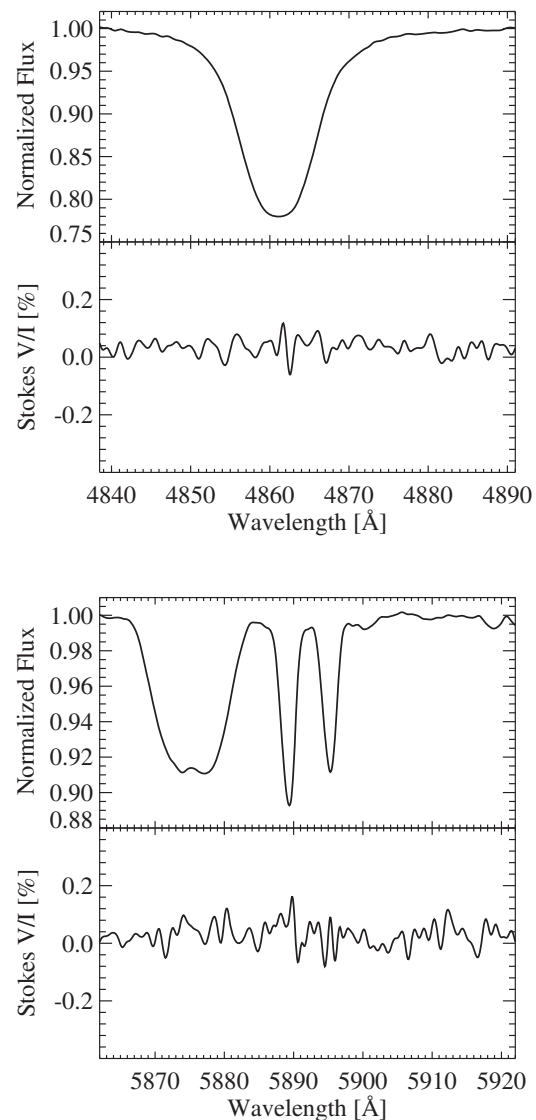

Fig. 2 Stokes I and V spectra of ζ Oph in the spectral regions around Hβ (top) and the Na I doublet (bottom).

In Fig. 3 we present time series of Stokes I spectra corresponding to our data set of six sub-exposures in the region around He II 4686 Å and He I 4713 Å. Although the time lapse between the observations of the first pair and the last pair is only 13 minutes, some small line profile variations in the He I line are already detectable at such short time scales.

The only other measurements of the magnetic field in ζ Oph have been presented by Schnerr et al. (2008) who used the MuSiCoS spectropolarimeter to derive Stokes I and V spectra with the Least Square Deconvolution method. No longitudinal magnetic field was detected in this star at a level more than 3σ. However, the measurement errors in their observations were in the range from 700 G to more than 3 kG.

Massive stars usually end their evolution with a final supernova explosion, producing neutron stars or black holes.
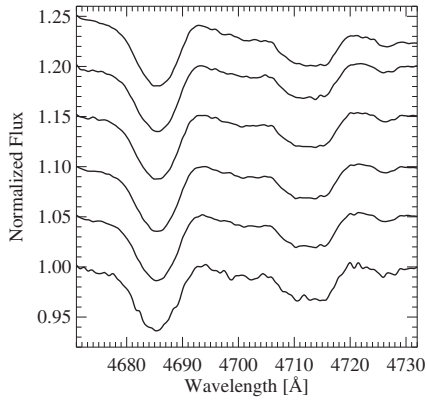
Fig. 3 Six Stokes I spectra corresponding to six sub-exposures in the region around He II 4686 Å and He I 4713 Å. Small line profile variations in the He I line are already detectable on the time scale of only 13 min.

The initial masses of these stars range from $\sim$8–10 $M_\odot$ to 100 $M_\odot$ or more, which correspond to spectral types earlier than about B2. Contrary to the case of Sun-like stars, the magnetic fields of stars on the upper main sequence (Ap/Bp stars), white dwarfs, and neutron stars are dominated by large spatial scales and do not change on yearly time scales. In each of these classes there is a wide distribution of magnetic field strengths, but the distribution of magnetic fluxes appears to be similar in each class, with maxima of $\Phi_{\mathrm{max}} = \pi R^2 B \sim 10^{27-28}$G cm^2 (Reisenegger 2001; Ferrario & Wickramasinghe 2005), arguing for a fossil field whose flux is conserved along the path of stellar evolution. According to Reisenegger (2009) the magnetic fluxes have possibly been generated on or even before the main-sequence stage and then inherited by the compact remnants.

The magnetic field strength of the pulsar PSR B1929+10 is 0.5129×10^{12} Gauss. Assuming simple conservation of magnetic flux we obtain a field strength of just a few Gauss for the more massive pulsar progenitors. For ζ Oph, which is supposed to be formed in a binary SN, sharing the same environment with the SN progenitor, the expected field strength would be of the order of 10 G. This value is notably lower than our current measurement, possibly indicating that either the magnetic field of this middle-aged pulsar has significantly decayed during the few Myrs after the SN explosion or other mechanisms play a role in the generation of magnetic fields in O-type stars.

3 Discussion

ζ Oph has been extremely well studied in all wavelength ranges, from the X-ray by all major X-ray satellites (with the exception of *XMM-Newton*) to the infrared region with *Spitzer*. In view of the detection of a magnetic field on ζ Oph reported in this work, we review its X-ray properties with

the aim to understand whether the X-ray emission of ζ Oph is dominated by magnetic or wind instability processes.

Babel & Montmerle (1997) studied the case of a rotating star with a dipole magnetic field sufficiently strong to confine stellar wind. The magnetic field locally dominates the bulk motion of stellar wind, when the ratio of magnetic to kinetic energy density, $B^2/\mu_0 \rho v^2 > 1$, where v is the supersonic flow speed. A collision between the wind streams from the two hemispheres in the closed magnetosphere leads to a strong shock and X-ray emission.

MHD simulations in the framework of this magnetically confined wind shock (MCWS) model were performed by ud-Doula & Owocki (2002) and Gagné et al. (2005). Using their notation, the wind is confined when $\eta_* \equiv (R_*^2 B^2)(\dot{M}v_\infty)^{-1} > 1$. New observations are required to establish whether the magnetic field of ζ Oph is a dipole. However, for the purpose of this discussion, let us assume that the field has an average strength of 150 G. Using the stellar parameters of ζ Oph as inferred by Marcolino et al. (2009), we estimate $\eta_*(\zeta \text{ Oph}) \sim 10^3$, i.e. the magnetic field should dominate the wind motion up to the Alfvén radius that is located at $\lesssim 10\,R_*$. In this case, the X-ray emission should mainly originate from the MCWS.

The MCWS model predicts that the X-ray emitting plasma should be located at a few R_* from the photosphere; that the X-ray emission lines should be narrow; that the X-ray luminosity should be higher and the spectrum harder than in non-magnetic stars; that in oblique magnetic rotators the X-ray emission should be modulated periodically as a consequence of the occultation of the hot plasma by a cool torus of matter, or by the opaque stellar core.

The lines of He-like ions observed in X-ray spectra are useful to derive the location of the line formation region in hot stars because forbidden line emission is depressed by ultraviolet pumping. The latter depends on the distance to the stellar photosphere (Gabriel & Jordan 1969; Blumenthal et al. 1972). The Si XIII line observed in the *Chandra* HETGS/MEG spectrum is shown in Fig. 4. The prominent forbidden line can easily be distinguished in this figure, while normally forbidden lines are strongly suppressed in the spectra of OB-type stars. The presence of the forbidden line implies that the line formation region is located far from the photosphere, so that the radiative excitation does not lead to the depopulation of the corresponding metastable energy levels. Waldron & Cassinelli (2008) found that the Si XIII line is formed at $1.8 \pm 0.7\,R_*$ in ζ Oph and that other He-like lines are formed even further out in the wind. Interestingly, the strong forbidden Si XIII line is also observed in the *Chandra* spectrum of the magnetic star τ Sco. Cohen et al. (2005) derive a Si XIII line formaiton radius for τ Sco in the range between 1.1 R_* and 1.5 R_*. These radii of line formation are smaller than those found in the prototypical MCWS model object θ^1 Ori C, $3.4 \pm 0.8\,R_*$ (Waldron & Cassinelli 2008).

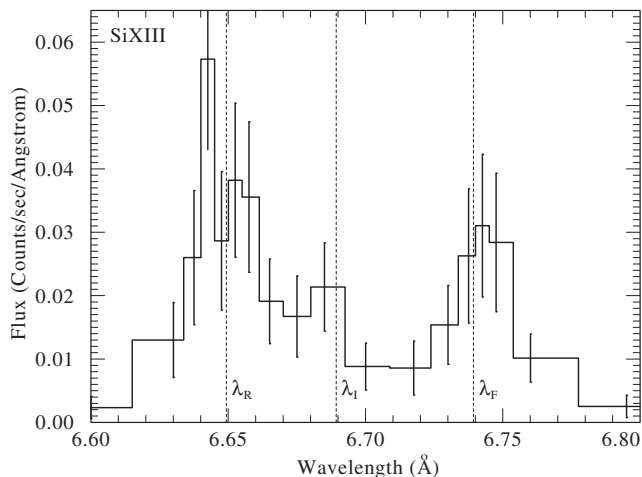Oskinova et al. (2006) studied the *Chandra* spectrum of ζ Oph among other O-type stars. They found that the X-ray

Fig. 4 The Si XIII line observed in the spectrum of ζ Oph (co-added MEG ± 1). Vertical dashed lines indicate the rest-frame wavelength: λ_R – resonant line, λ_I – sum of intercombination lines, λ_F – forbidden line. The rest-frame wavelengths are corrected for the radial velocity taken from Hoogerwerf et al. (2001).

emission lines in this star are narrow and that the signatures of wind absorption on line profiles are weak. Figure 5 shows the Fe XVII and Ne X lines as measured by *Chandra* plotted over units of the wind terminal velocity, $v_\infty = 1550$ km s^{-1}. The lines are only slightly broadened, if at all.

The X-ray luminosity of ζ Oph, $L_X = 1.2 \times 10^{31}$ erg s^{-1} and the ratio $L_X/L_{bol} = 4 \times 10^{-8}$ are quite usual among late type OV stars (Oskinova et al. 2006). Adopting the mass-loss rate from ζ Oph as $\lesssim 1.8 \times 10^{-7} \, M_\odot$ yr^{-1}, Oskinova et al. (2006) noticed that in ζ Oph the ratio of X-ray to wind mechanical luminosity L_{mech} ($\dot{M}v_\infty^2/2$), $L_X/L_{mech} \gtrsim 8.5 \times 10^{-5}$, is a few times higher than in other single O-type stars. This may be related to the lower wind opacity in ζ Oph, or it may hint at some additional mechanism of X-ray generation besides the intrinsic wind shocks.

From their analysis of *Chandra* spectra, Zhekov & Palla (2007) derived the differential emission measure (DEM) for ζ Oph among other OB stars in their sample. They found that in ζ Oph the DEM sharply peaks at about 6 MK. While this is a significantly lower temperature than found for the DEM peak in case of θ^1 Ori C (50 MK), it is higher than found for other stars of similar spectral types ($\sim$3 MK). Thus, considering the X-ray temperature of ζ Oph, it is not straightforward to attribute its X-ray emission to the MCWS. On the other hand, recent studies of O stars with detected magnetic fields (e.g., HD 191612, HD 108) show that their X-ray properties are diverse (Nazé et al. 2004, 2010) and may be difficult to fully reconcile with the predictions of the MCWS model.

Clearly, new observations are needed to better understand the magnetic field of ζ Oph and its link with the X-ray emission from this star.
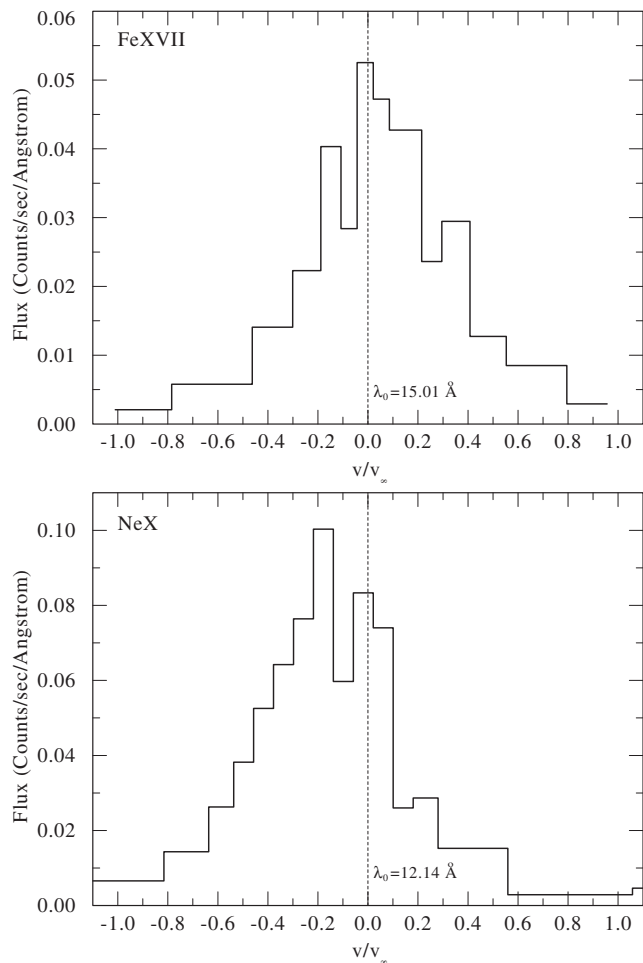
Fig. 5 Fe XVII (upper panel) and Ne X (lower panel) lines observed in the spectrum of ζ Oph (co-added MEG ± 1). Vertical dashed lines indicate the rest-frame wavelength, corrected for the radial velocity.

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