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Discovery of two magnetic massive stars in the Orion Nebula Cluster: a clue to the origin of neutron star magnetic fields?

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ABSTRACT

The origin of the magnetic fields in neutron stars, and the physical differences between magnetars and strongly magnetized radio pulsars are still under vigorous debate. It has been suggested that the properties of the progenitors of neutron stars (the massive OB stars), such as rotation, magnetic fields and mass, may play an important role in the outcome of core collapse leading to Type II supernovae. Therefore, knowing the magnetic properties of the progenitor OB stars would be an important asset for constraining models of stellar evolution leading to the birth of a neutron star. We present here the beginning of a broad study with the goal of characterizing the magnetic properties of main-sequence massive OB stars. We report the detection of two new massive magnetic stars in the Orion Nebula Cluster: Par 1772 (HD 36982) and NU Ori (HD 37061), for which the estimated dipole polar strengths, with 1σ error bars, are 1150^{+320}_{-200} and 620^{+220}_{-170} G, respectively.

Key words: stars: early-type – stars: magnetic fields – stars: neutron – pulsars: general.

1 INTRODUCTION

Strong, organized magnetic fields are observed to exist in some main-sequence (MS) stars of spectral type A, B and O. Two general models have been proposed to explain the presence of these magnetic fields.

(i) In the dynamo model, the field is generated by a dynamo mechanism, occurring classically in the convective regions or induced by strong shear during differential rotation.

(ii) In the fossil model, the field is a remnant from a dynamo active during a previous evolutionary phase, or swept up from the interstellar medium (ISM) during star formation. This scenario implies that the field must somehow survive the various internal structural changes encountered during stellar evolution. The magnetic flux is usually assumed to be conserved to some extent.

Although dynamo models reproduce well the characteristics of late-type MS stars and giants, they fail to explain the fields of magnetic early-type stars, as their envelopes are primarily radiative. Some models of dynamo activity in the small convective cores of those stars have been put forward, but they still have fundamental difficulties reproducing the observed field characteristics (Charbonneau & MacGregor 2001). Their simple magnetic geometries, lack of significant mass–field strength or period–field strength relation, and the fact that the observed characteristics of magnetic fields in pre-MS Herbig Ae/Be stars (Wade et al. 2005; Catala et al. 2007; Folsom et al. 2007; Wade et al. 2007; Alecian et al. 2008) are qualitatively identical to those of their MS descendants, point towards a fossil origin. Furthermore, the incidence, geometries and strengths of white dwarf magnetic fields are at least qualitatively compatible with evolution from magnetic MS A and B stars, suggesting that the fields of white dwarfs may also be of fossil origin (e.g. Wickramasinghe & Ferrario 2005).

In more massive OB stars, magnetic fields have only been discovered recently, mostly via clues provided by unusual X-ray properties. Traditionally, the X-ray emission from O and B stars, with a typical level $L_X/L_{bol} \sim 10^{-7}$, has been explained by radiative instabilities via a multitude of shocks in the wind (Lucy & White 1980; Owocki & Cohen 1999). However, the very strong and rotationally modulated X-ray emission of the brightest Trapezium star, θ^1 Ori C [O7, $P = 15.4$ d, Gagné et al. (1997)] was explained by Babel & Montmerle (1997) in terms of the 'magnetically confined wind shock' model (MWCS). In this model, the stellar magnetic field is sufficiently strong, and the radiative wind is sufficiently weak, to allow a dipolar magnetic field to confine the outflowing wind in the

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immediate-circumstellar environment, resulting in a closed magnetosphere with a large-scale equatorial shock which heats the wind plasma. In this way, the X-ray emission is enhanced and may be modulated by stellar rotation. The MCWS model provided a quantitative prediction of a magnetic field in θ^1 Ori C; such a field (1.1 ± 0.1 kG) was subsequently discovered by Donati et al. (2002). At the present time, θ^1 Ori C and HD 191612 (1.5 kG, Donati et al. 2006) are the only known O-type stars with directly detected magnetic fields. However, it has been speculated that magnetism may be widespread among massive stars. Some clues to the presence of magnetic fields come from X-ray photometry and spectroscopy (Stelzer et al. 2005; Waldron & Cassinelli 2007), non-thermal radio synchrotron emission (Schnerr et al. 2007) and cyclical variations of ultraviolet (UV) wind spectral lines (Kaper et al. 1996; Fullerton 2003). Hence, this lack of magnetic field detection may well be due to the fact that direct measurement of magnetic fields present in the atmosphere of O-type and early B-type stars is extremely difficult. These difficulties arise from the small number of photospheric lines present in the optical spectrum and the large intrinsic width of the lines, worsened by the usual fast rotation of these stars.

Neutron stars, evolved from the massive OB stars, are characterized by a wide range of magnetic field strengths. Inferred from spin-down rates of radio pulsars, their strengths are in the range of 10^{11}–10^{14} G. Two groups of neutron stars, the anomalous X-ray pulsars (AXPs) and the soft gamma repeaters (SGRs) host super-strong magnetic fields (10^{14}–10^{15} G), and are referred to as magnetars. It is thought that the physical distinction between radio pulsars and magnetars is not simply the dipole field strength, as there is a small population of radio pulsar with fields at a magnetar like level, but that does not show the same X-ray characteristics (Kaspi & McLaughlin 2005). There is some observational evidence that neutron stars may evolve from stars as massive as 45 $M_\odot$, and that many magnetars are linked strongly to these massive stars (Gaensler et al. 2005; Muno et al. 2006).

The magnetic flux of θ^1 Ori C (45 $M_\odot$) is $(7 \pm 3) \times 10^{27}$ G cm^2 (using the stellar radius from Simón-Díaz et al. (2006). This magnetic flux is roughly of the same scale as the highest field magnetar SGR 1806−20[1] ($\sim 3 \times 10^{28}$ G cm^2, assuming a 10 km radius). Therefore, in principle, there is enough magnetic flux present in a massive magnetic star like θ^1 Ori C to explain the super-strong fields seen in some neutron stars, under the simple assumption that the magnetic flux is completely conserved during its post-MS stellar evolution and transformation into a neutron star. Furthermore, provided that OB star fields are remnants from the interstellar medium (ISM), the fossil hypothesis could provide a powerful explanation of the wide range of magnetic fields present in neutron stars (Ferrario & Wickramasinghe 2006).

On the other hand, it has been suggested that neutron star magnetic fields could instead be generated during the core collapse itself, by a dynamo mechanism induced by differential rotation (Braithwaite 2006). Present studies assume that any primordial fields present in the progenitor star are weak enough to be expelled by the dynamo process. However, if the initial field is strong enough, the evolution will be different, as this field is likely to interfere with differential rotation and therefore with the dynamo process itself (Heger, Woosley & Spruit 2005).

Hence, there seem to be three fundamental parameters that may play key roles in the origin of neutron star magnetic fields, and in the explanation of the differences between magnetars and radio pulsars: the primordial magnetic field of the progenitor, the rotation of the star and its mass. Therefore, knowing the magnetic properties of the progenitor OB stars would be an important asset for constraining models of stellar evolution leading to neutron star birth. Many observational efforts are underway to characterize magnetic fields throughout massive star evolution. We present here the beginning of a broad study with the goal of characterizing the magnetic properties of MS massive OB stars.

The Orion Nebula Cluster (ONC) presents a unique opportunity to characterize the magnetic fields of a nearby coevolved and coenvironmental population of massive OB stars. Furthermore, a *Chandra* large program, the *Chandra* Orion Ultradeep Project (COUP) was dedicated to observe the ONC in X-ray (Stelzer et al. 2005), enabling a study of the connections between stellar winds, magnetic fields and X-rays emission, which will be presented in a subsequent letter. The ONC contains nine massive OB stars. They range from B3 V ($\sim$8 $M_\odot$) to O7 V ($\sim$40 $M_\odot$), approximately the mass range from which neutron stars are thought to be formed. In this letter, we report the detection of two new massive magnetic stars in the ONC.

2 OBSERVATIONS

We conducted spectropolarimetric observations with the ESPaDOnS spectropolarimeter at CFHT in 2006 January and 2007 March. We obtained high resolution ($R \sim 65\,000$) and high signal-to-noise ratio (S/N) spectra of eight of the nine massive OB stars of the ONC, in both epochs. Additional measurements of θ^1 Ori C and Par 1772 were taken with ESPaDOnS in 2007 December and with ESPaDOnS's twin Narval, installed at TBL, France, in 2007 November, respectively.

A complete circular polarization observation consists of series of four sub-exposures between which the polarimeter quarter-wave plate is rotated back and forth between position angles, which make it possible to reduce systematic errors. For a complete description of observation procedures and reduction procedures with the ESPRIT reduction package (which is fundamentally the same as the LIBRE-ESPRIT package provided by CFHT), see Donati et al. (1997).

In order to increase the magnetic sensitivity of our data, we applied the least-squares deconvolution (LSD) procedure (Donati et al. 1997), which enables the simultaneous use of many lines present in a spectrum to detect a magnetic field Stokes V signature. The line masks were carefully chosen to exclude Balmer lines and any other lines blended with them. Using the LSD technique, we found clear Stokes V signatures for three stars: the previously detected θ^1 Ori C, as well as Par 1772 (HD 36982) and NU Ori (HD 37061). The LSD profiles for these three stars are shown in Fig. 1. We used the statistical test described by Donati et al. (1997) to diagnose the presence of a signal in either mean Stokes V or diagnostic null profiles. A signal is unambiguously detected inside the spectral line range whenever the associated detection probability is larger than 99.999 per cent (corresponding to a false alarm probability smaller than 10^{-5}). The associated longitudinal field can be estimated with the Stokes I and V profiles (e.g. Wade et al. 2000). It is important to note that the longitudinal field is only given as an indicator of the field strength and not the main diagnostic for the presence of a magnetic field, because a magnetic configuration with a null longitudinal component can still produce a non-null Stokes V signature. Table 1 presents an observing log for the detected stars, along with the detection probability inside the spectral line range and the derived longitudinal field component.

[1] http://www.physics.mcgill.ca/∼pulsar/magnetar/main.html

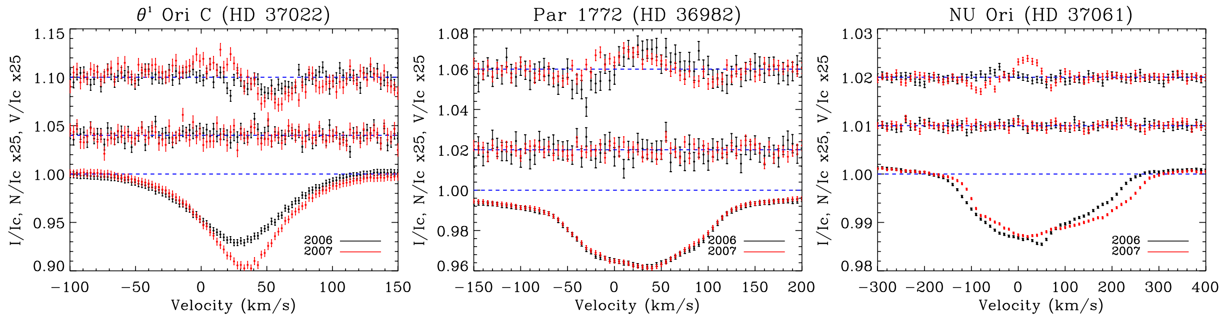

Figure 1. Least-squares deconvolved profiles for θ^1OriC (left-hand panel), Par1772 (middle panel) and NU Ori (right-hand panel). The curves are the mean Stokes I profiles (bottom panel), the mean Stokes V profiles (top panel) and the N diagnostic null profiles (middle panel), black for 2006 January and red for 2007 March.

Table 1. Observation log for the detected stars, along with detection diagnostics and derived longitudinal field components.

Star	Date (UT)	HJD	Total exposure time (s)	Peak snr[a]	LSD snr[a]	Detection	P (per cent)	B_l (G)
θ^1OriC	2006 January 09	53 744.792	4800	1700	3000	Marginal	99.98	131 ± 56
(O7V)	2007 March 10	54 168.835	3200	1600	2600	Definite	>99.999 99	471 ± 53
	2007 December 21	54 456.748	3200	2000	3700	None	66.8	−53 ± 44
	2007 December 22	54 457.748	3200	1800	3200	None	93.2	122 ± 50
Par 1772	2006 January 12	53 747.728	9600	440	2000	Definite	99.999 97	−249 ± 77
(B2V)	2007 March 07	54 166.699	9600	760	3400	Definite	>99.999 99	84 ± 45
	2007 November 11	54 416.550	6000	370	1600	Marginal	99.93	−321 ± 95
NU Ori	2006 January 12	53 747.852	9600	1300	14 000	None	50.5	82 ± 52
(B0.5V)	2007 March 08	54 167.703	9600	1500	15 000	Definite	>99.999 99	−165 ± 56

[a]Per 1.8 km s^{-1} pixel for the summed spectra.

(i) θ^1 *Ori C* is the canonical example of a magnetic O star showing rotationally modulated spectral and X-ray variations caused by magnetic confinement of its stellar wind (Babel & Montmerle 1997; Donati et al. 2002). This most massive star of the Trapezium is a speckle binary with a 0.037 arcsec separation, composed of a 45 $M_{\odot}$ primary (O7V) and a $\gtrsim 6\,M_{\odot}$ secondary (Schertl et al. 2003). Optical, UV and X-ray features all vary according to a 15.422 ± 0.002-d period (Stahl et al. 1996; Gagné et al. 1997). We obtained four observations of this star, and according to this ephemeris, our observations correspond to phase 0.49, 0.05, 0.66 and 0.72 for 2006 January, 2007 March and the two observations of 2007 December, respectively. The corresponding derived longitudinal fields are in good agreement with previous spectropolarimetric measurements (Donati et al. 2002; Wade et al. 2006), and therefore with their derived dipolar field strength of about 1.1 kG (Fig. 2).

(ii) *Par 1772* is an MS (or possibly pre-MS) B2 star (∼6 $M_{\odot}$), with a projected rotational velocity of 80 ± 20 km s^{-1} (Wolff, Strom & Hillenbrand 2004). The 2007 March Stokes V signature is a good example of a cross-over signature, where the longitudinal field component is nearly null (here, 84 ± 45 G), but the symmetry of the polarized Zeeman components is broken by Doppler shifts induced by stellar rotation. The measurement of 91 ± 193 G obtained by Bagnulo et al. (2006) with FORS1 at Very Large Telescope (VLT) was likely at such a cross-over phase, the magnetic field going undetected because of the lower spectral resolving power of that instrument.

(iii) *NU Ori* is a triple system, containing a B0.5V primary (14 $M_{\odot}$), along with a spectroscopic companion of ∼3 $M_{\odot}$ (component C, 80 m separation) and a ∼1 $M_{\odot}$ visual companion (component B) with a 471 ± 17 m separation (Preibisch et al. 1999). The primary is a rapidly rotating star, with a $v \sin i = 225 \pm 50$ km s^{-1}

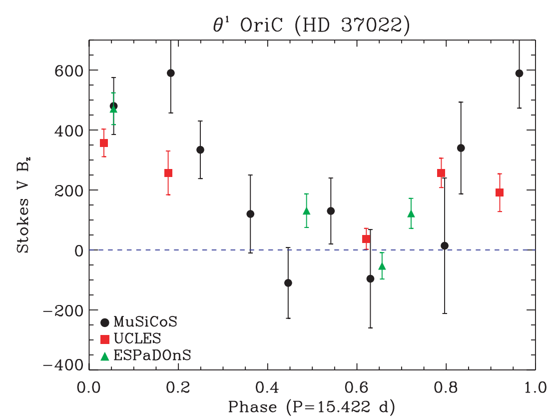

Figure 2. Longitudinal magnetic field measurements for θ^1 Ori C. The Multi-Site Continuous Spectroscopy (MuSiCoS) measurements (back circles) are from Wade et al. (2006), the UCL Echelle Spectrograph (UCLES) measurement (red squares) are from Donati et al. (2002) and the ESPaDOnS measurements (green triangles) are from this work.

(Wolff et al. 2004), making it the most rapidly rotating early-B star with a detected field. Although such high rotational velocity usually occurs only in Be stars, the small and narrow emission in Hα, β and γ seems more related to nebular emission than to a Be behaviour. While there was no formal signal detection for the 2006 January observation, the 2007 March observation showed a definite signal detection. A close inspection of the intensity spectrum revealed the weak, sharp spectral lines of the spectroscopic companion. The width of the Stokes V signatures compared to the width of the companion spectral lines rules out associating the polarization

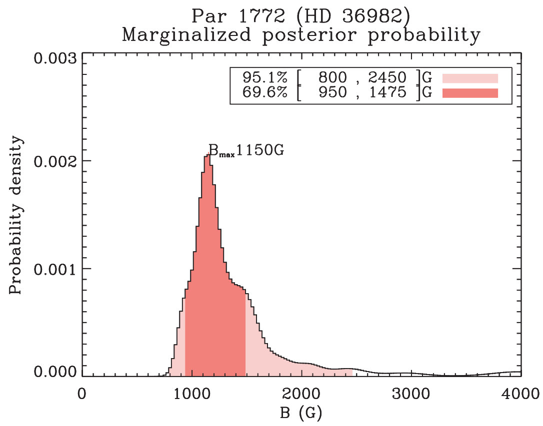

Figure 3. Marginalized probability densities of the dipole polar field strength for Par1772. The magnetic field strength 95 per cent credible region is filled in light colour. The 68.3 per cent credible region used to calculate the 1σ error bars is filled in dark colour.

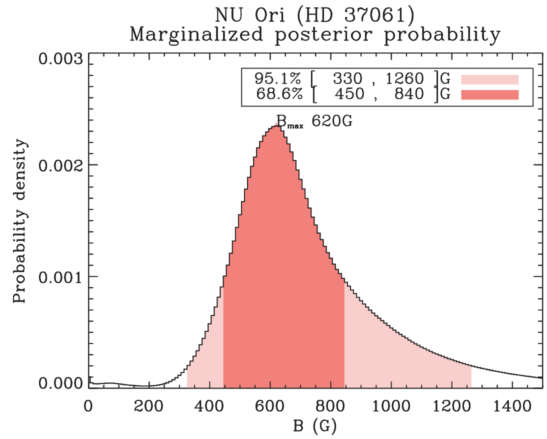

Figure 4. The same as Fig. 3 for NU Ori.

signature with the companion – the magnetic field and the profile asymmetries are clearly intrinsic to the primary.

3 SURFACE MAGNETIC FIELDS

In order to extract the surface field characteristics from the observed Stokes V profiles, we compared them with theoretical profiles for a large grid of dipolar magnetic field configurations, calculated with the polarized LTE radiative transfer code ZEEMAN2 (Landstreet 1988; Wade et al. 2001). We sampled the four-dimensional parameter space (i, β, φ, B) which describes a centred dipolar magnetic configuration. In such a model, i is the projected inclination of the rotation axis to the line of sight, β is the obliquity of the magnetic axis with respect to the rotation axis, φ is the rotational phase and B is the polar field strength at the stellar surface. For each configuration, we calculated the reduced χ^2 of the model fit to the observed mean Stokes V profiles. Assuming that only the phase may change between two observations of a given star, the goodness-of-fit of a given rotation-independent (i, β, B) configuration is expressed in terms of Bayesian probability density. This ensures that a good magnetic (i, β, B) configuration can produce Stokes V profiles that fit all observations, as the rotational period is not known with enough accuracy to determine a priori the phase difference. Any features that cannot be explained by the rotating dipole model are treated formally as additional Gaussian noise, which will lead to the most conservative estimates of the parameters, according to the maximum entropy principle.

We can determine the probability density of the field strength by marginalizing over inclination and obliquity. We then extract a 95 per cent credible region for the surface dipole field strength of each star with the technique described by Gregory (2005). Figs 3 and 4 show the resulting probability density functions for Par 1772 and NU Ori, respectively. The 95 per cent credible regions are 800, 2450 G for Par 1772 and 330, 1260 G for NU Ori. The inferred values of the dipole polar strength, with 1σ error bars, are then 1150^{+320}_{-200} and 620^{+220}_{-170} G, respectively.

4 DISCUSSION

As an illustrative example of the potential of these new data to constrain models of neutron star field origins, we can compare them with the predictions of Ferrario & Wickramasinghe (2006) of the magnetic field distribution of massive stars (8–45 $M_\odot$) on the MS. This distribution is based on the observed properties of radio pulsars from the 1374-MHz Parkes Multibeam survey of isolated radio pulsar, assuming a simple fossil field origin with a complete conservation of magnetic flux. They obtained a continuous magnetic field distribution in the progenitor OB stars, peaking at ∼46 G with 5 per cent[2] of the stars having a field in excess of 1 kG.

Of course, our sample contains only eight stars, but we can still make some rough comparisons. Taking the predicted field strength distribution, we assume that it is the true parent distribution from which we draw a random sample of eight stars. We define three possible outcomes: 0 – 500, 500 – 1000 and over 1000 G, with respective probabilities derived from the parent theoretical distribution. According to the multinomial distribution, the probability of obtaining the distribution of magnetic field strengths observed in the ONC is about 1 per cent.

This result might be interpreted, at first glance, to suggest that massive OB stars are more magnetic than it would be required to explain the magnetic fields of radio pulsars. However, some points are important to consider: (i) the sample of observed stars may not be representative of a general parent distribution, as all the stars come from the same cluster. This region could be unusually magnetic, especially if the fields of the OB stars themselves are also of fossil origin from the ISM. (ii) The assumed parent distribution is not, in fact, the true parent distribution because some assumptions are incorrect, or some elements are missing from the model. Examples of such missing physics might be partial flux conservation or the influence of dynamo processes during core collapse.

In order to better explore these possibilities, a larger sample of OB stars, from clusters and field, must be studied in order to increase the population of neutron star progenitors with known magnetic properties. Our team has undertaken an extensive spectropolarimetric study of massive stars in other young star clusters to provide these important data.

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[2] Although Ferrario & Wickramasinghe (2006) state 8 per cent, recalculation based on the detailed model distribution provided by L. Ferrario gives 5 per cent.

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