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Discovery of a strong magnetic field on the O star HD 191612: new clues to the future of θ^1 Orionis C[★]

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ABSTRACT

From observations made with the ESPaDOnS spectropolarimeter, recently installed on the 3.6-m Canada–France–Hawaii Telescope, we report the discovery of a strong magnetic field in the Of?p spectrum variable HD 191612 – only the second known magnetic O star (following θ^1 Ori C). The stability of the observed Zeeman signature over four nights of observation, together with the non-rotational shape of line profiles, argues that the rotation period of HD 191612 is significantly longer than the 9-d value previously proposed. We suggest that the recently identified 538-d spectral variability period is the rotation period, in which case the observed line-of-sight magnetic field of -220 ± 38 G implies a large-scale field (assumed dipolar) with a polar strength of about -1.5 kG. If confirmed, this scenario suggests that HD 191612 is, essentially, an evolved version of the near-zero-age main-sequence magnetic O star θ^1 Ori C, but with an even stronger field (about 15 kG at an age similar to that of θ^1 Ori C). We suggest that the rotation rate of HD 191612, which is exceptionally slow by accepted O-star standards, could be due to angular momentum dissipation through a magnetically confined wind.

Key words: techniques: polarimetric – stars: early-type – stars: individual: HD 191612 – stars: magnetic fields – stars: rotation – stars: winds, outflows.

1 INTRODUCTION

The magnetic fields of O stars can strongly impact on the physics of the stellar interiors (e.g. Spruit 2002) and atmospheres (e.g. Babel & Montmerle 1997), and hence on the long-term evolution of the stars (e.g. Maeder & Meynet 2003, 2004). However, quantifying such effects critically depends on our knowledge of the properties of such fields.

From a theoretical point of view, the origin of magnetic fields in O stars is still rather uncertain. One possibility is that they are fossil remnants of the star formation stage, as proposed for magnetic

chemically peculiar Ap and Bp stars (e.g. Mestel 1999); if this were the case, we would expect to find about 10 per cent of O stars with dipolar-type magnetic topologies with super-equipartition strengths of at least several hundred G. Another option, gaining recent support among theoreticians, is that such fields are produced by dynamo processes, within the convective cores (Charbonneau & MacGregor 2001), or in a putative subsurface shear layer (MacDonald & Mullan 2004; Mullan & MacDonald 2005); magnetic topologies would then depend on rotation rate and feature a significant toroidal component.

From an observational point of view, however, very few direct constraints exist on the strength and topology of magnetic fields in O stars, even though such fields are often invoked as a potential explanation for many otherwise enigmatic phenomena (e.g. the unexpected properties of the X-ray spectra: Cohen et al. 2003). While several attempts have been made to characterize the fields that could be hosted at the surfaces of bright, archetypal O stars such as ζ Pup and ζ Ori, no detections have yet been obtained, with only one exception: the very young object θ^1 Ori C (Donati et al. 2002). One reason for this is that absorption lines of O stars are both relatively few in number in the optical, and generally rather broad (because

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of rotation or to some other type of as yet unknown macroscopic mechanism: e.g. Howarth et al. 1997), decreasing dramatically the size of the Zeeman signatures that their putative fields can induce.

The recent discovery by Walborn et al. (2004) that the Of?p star HD 191612 varies between spectral types O6 and O8 with an apparently strict periodicity is significant in this context. The H α and He I lines show a particularly strong modulation, reminiscent of that seen in θ^1 Ori C (Stahl et al. 1996); HD 191612 thus appears at first glance as a very good candidate for the detection and investigation of a hot-star magnetic field. However, the derived period of the spectral variability, 538 d, is so long (by O-star standards) that rotational modulation was considered unlikely by Walborn et al. Instead, they preferred to associate the spectroscopic variability with an eccentric binary orbit, hypothesizing that tidally induced non-radial pulsations (NRP) at periastron may induce periodically enhanced mass loss.

However, the lack of any clear orbital radial-velocity variations, down to a level of a few km s⁻¹ (Walborn et al. 2003), is a significant hurdle to this model, especially since rather large eccentricity is implied by the NRP hypothesis. Thus, even though very slow rotation is at odds with conventional wisdom, the possibility that the observed variability may be related to rotational modulation of a magnetic star is by no means excluded. Motivated by its similarities to θ^1 Ori C, we therefore included HD 191612 in a list of candidates to search for magnetic fields in O-type stars using ESPaDOnS (Donati et al., in preparation), the new, high-efficiency spectropolarimeter recently installed on the 3.6-m Canada–France–Hawaii Telescope (CFHT).

In this Letter, we first present the observations and the Zeeman detection that we obtained (Section 2). We then review the constraints on rotation (Section 3), perform simple modelling of our observations (Section 4), and discuss the implications of our results for rotational evolution of hot stars with strong radiation-driven winds (Section 5).

2 OBSERVATIONS

Spectropolarimetric observations of HD 191612 were collected in 2005 June, as part of a four-night run aimed at investigating the magnetic fields of hot stars. (Results obtained on the other stars observed in the same run will be published separately.) At the time, the instrument was suffering a 1.3-mag light loss compared with the optimal performance obtained during the engineering runs (Donati et al., in preparation). This problem was not evident until the time of the run; now fixed, it turned out to be due to severe damage to the external jacket of optical fibres linking the polarimeter with the spectrograph (probably caused during movement of the instrument up and down from the Cassegrain focus). Current ESPaDOnS performance is therefore significantly better than the results given here imply.

HD 191612 was observed each night; altogether, 13 circular polarization sequences, each consisting of four individual subexposures taken in different polarimeter configurations, were obtained [see Donati et al. (in preparation) for details]. All frames were processed using LIBRE ESPRIT (Donati et al. 1997; Donati et al., in preparation), a fully automatic reduction package installed at CFHT for optimal extraction of ESPaDOnS spectra. The peak signal-to-noise ratios per 2.6 km s⁻¹ velocity bin range from 200 to 450, depending mostly on weather conditions (see Table 1).

Least-squares deconvolution (LSD: Donati et al. 1997) was applied to all observations. This requires the input of a line list, which was constructed manually to include the few moderate to strong

Table 1. Journal of observations. Columns 1–5 list the date, heliocentric Julian date, UT time, exposure time and peak signal to noise ratio (per 2.6 km s⁻¹ velocity bin) for each observation. The last column lists the rms noise level (relative to the unpolarized continuum level (I_c) and per 41.6 km s⁻¹ velocity bin) in the circular polarization profile produced by LSD (Section 2).

Date (2005)	HJD (245 3000+)	UT (h:m:s)	t_{exp} (s)	S/N	σ_{LSD} ($10^{-4} I_c$)
June 22	545.02530	12:30:55	4 × 600	340	2.6
June 22	545.05519	13:13:57	4 × 600	200	4.5
June 23	545.98583	11:33:59	4 × 600	440	1.9
June 23	546.01569	12:16:59	4 × 600	450	1.8
June 23	546.04559	13:00:02	4 × 600	440	1.8
June 23	546.07596	13:43:46	4 × 600	420	1.9
June 24	546.97492	11:18:11	4 × 600	440	1.9
June 24	547.00479	12:01:12	4 × 600	430	1.9
June 24	547.03466	12:44:12	4 × 600	420	1.9
June 25	547.98896	11:38:19	4 × 600	280	3.0
June 25	548.01933	12:22:03	4 × 600	390	2.1
June 25	548.04987	13:06:02	4 × 600	380	2.3
June 25	548.08030	13:49:50	4 × 600	330	2.9

Table 2. Lines used for LSD. The line depths (column 3) were directly measured from our spectra while the Landé factors (column 4) were derived assuming LS coupling.

Wavelength (nm)	Element	Depth (I_c)	Landé factor
402.6187	He I	0.210	1.167
419.9839	He II	0.125	1.000
447.1473	He I	0.250	1.100
451.0963	N III	0.051	1.100
451.4854	N III	0.072	1.214
454.1591	He II	0.175	1.000
471.3139	He I	0.095	1.250
501.5678	He I	0.085	1.000
541.152	He II	0.207	1.000
559.2252	O III	0.078	1.000
580.1313	C IV	0.172	1.167
581.1970	C IV	0.128	1.333

absorption lines that are present in the spectrum of HD 191612. As, essentially, we aim to probe the photosphere of HD 191612, lines appearing in emission (such as the N III lines at 463.41 and 464.06 nm) were not included, even though in some cases they may result from selective emission processes in or near the photosphere. The strong Balmer lines, all showing clear emission from the wind and/or circumstellar environment at the time of our observations, were also excluded from the list, as were other features showing P Cygni profiles (such as He II 468.57 nm and He I 587.56 nm). This left only 12 usable spectral lines, the characteristics of which are summarized in Table 2.

From those lines we produced a mean circular polarization profile (LSD Stokes V profile) as well as a mean unpolarized profile (LSD Stokes I profile) for each spectrum. Given the breadth of the spectral lines of HD 191612 (average full width at half-depth is ~ 150 km s⁻¹), the LSD profiles were produced on a spectral grid with a velocity bin of 41.6 km s⁻¹; as this bin size is comparable to the typical broadening of intrinsic profiles from hot stars, no information from small-scale magnetic features potentially present

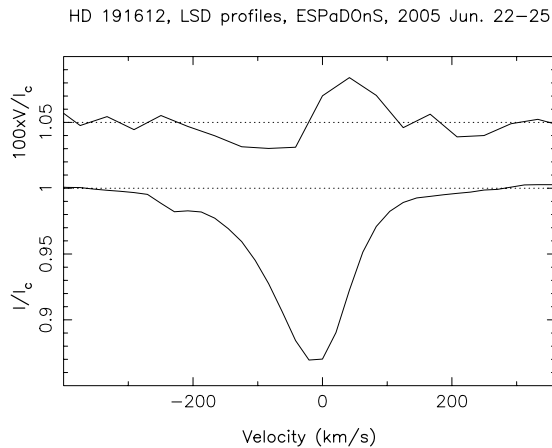


Figure 1. LSD circularly polarized (Stokes V) and unpolarized (Stokes I) profiles of HD 191612 (top and bottom curves respectively, normalized by the unpolarized continuum intensity I_c) on 2005 June 22–25. The mean polarization profile is expanded by a factor of 100 and shifted upwards by 1.05 for display purposes.

at the surface of the star is expected to be lost in this binning process (e.g. Donati et al. 2002). The resulting noise level in the LSD Stokes V profiles is about 0.02 per cent of the unpolarized continuum I_c per 41.6 km s^{-1} velocity bin (see Table 1).

Averaging together all LSD Stokes V profiles recorded on each of the four nights of observation (with weights proportional to the inverse variance of each profile) yields relative noise levels of 2.3, 0.9, 1.1 and 1.2 respectively, in units of $10^{-4} I_c$. Compared with a null-field, $V = 0$ profile, the resulting Stokes V signatures yield reduced χ^2 values of 0.9, 1.9, 1.6 and 1.5, respectively, implying clear Zeeman detections on each of the last three nights, although not the first. However, all four V profiles are mutually consistent. Averaging all V signatures yields a final noise level of $0.6 \times 10^{-4} I_c$, and a reduced χ^2 of 2.7. We can thus safely conclude that the star is magnetic; the resulting average Stokes V profile is shown in Fig. 1 and corresponds to a longitudinal field of $-220 \pm 38 \text{ G}$.

Note that, even though we excluded lines showing an obvious contribution from the wind, the LSD Stokes I profile is still significantly asymmetric (with the blue wing extending to higher velocities than the red one). Evidently, most ‘photospheric’ lines are likely to be affected to a small extent by the stellar wind. The Stokes V profile, showing a longer tail at blue wavelengths, is also slightly impacted by the same effect; however, adding or removing a few lines in the list does not change the overall shape of the detected Zeeman signatures (at the noise level), indicating that this perturbation has no significant consequences for the analysis presented here.

3 THE ROTATION PERIOD OF HD 191612

Walborn et al. (2004) inferred a rotation period for HD 191612 of $\sim 9 \text{ d}$, from an estimate of the radius and a measurement of 77 km s^{-1} for the line width parameter $v \sin i$. However, assuming that the magnetic topology of HD 191612 is essentially dipolar (as found for all other magnetic OB stars identified to date), a rotation period of 9 d would imply significant evolution of the observed (projected) field configuration over a 4-d run, provided that the magnetic dipole is not aligned with the rotation axis. We therefore conclude that the rotation period of the star is most probably significantly longer than 9 d, consistent with the fact that variability is detected neither in our unpolarized spectra, nor in previous spectroscopic

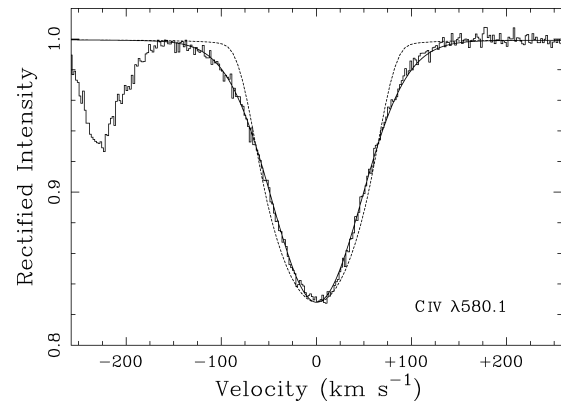


Figure 2. The C IV 580.1-nm profile, compared with models broadened by rotation ($v_e \sin i = 77 \text{ km s}^{-1}$, dashed line) and by isotropic Gaussian turbulence ($\sigma_v = 45 \text{ km s}^{-1}$, solid line). The feature at -230 km s^{-1} is a diffuse interstellar band.

data sets collected over intervals of a few days (e.g. Walborn et al. 2003).

This conclusion is further supported by the obviously non-rotational shape of the LSD Stokes I profile of HD 191612 (Fig. 1); if ‘turbulence’, of some as yet undetermined physical nature, dominates the line broadening, then clearly the line width parameter $v \sin i$ significantly overestimates the true projected equatorial rotation velocity, $v_e \sin i$ (cf. Howarth 2004), leading to an underestimate of the rotation period. To examine this possibility further we compare the observed profile of C IV 580.1 nm with some simple models (Fig. 2). This line is rather symmetrical, and is expected to form relatively deep in the atmosphere, so that it is probably more representative of the hydrostatic regions than is the LSD I profile. We took an OStar2002 model profile (Lanz & Hubeny 2003), with modest scaling to match the observed line depth, and applied a rotational convolution with $v_e \sin i = 77 \text{ km s}^{-1}$. The resulting profile does indeed match the observed line *width* quite well, but the overall match of the line shape is very poor. However, a simple model of Gaussian isotropic turbulence, with *zero* rotational broadening, while lacking any strong physical justification, none the less provides an excellent match to the observations.

Taken together, these arguments strongly suggest a rotation period significantly longer than the 9-d value previously proposed. We are therefore tempted to explore the consequences of identifying the rotation period of HD 191612 with the 538-d period recently identified for this star (Walborn et al. 2004), on which several spectroscopic indexes (and in particular $H\alpha$) are observed to vary. Although indicators of the implied *very* slow rotation are not yet overwhelming (e.g. constancy of the observed field could result from a dipole aligned with the rotation axis), the phenomenological similarities with the young O-type star $\theta^1 \text{ Ori C}$, now strengthened by the magnetic field that we have detected in HD 191612, indicate that the possibility of rotational modulation merits further consideration. Thus, while the proposal clearly needs further scrutiny (e.g. through the monitoring and potential detection of the rotational modulation of the Zeeman signature), we nevertheless now explore the consequences of a 538-d rotation period for HD 191612.

4 MODELLING THE MAGNETIC FIELD OF HD 191612

We propose that HD 191612, like $\theta^1 \text{ Ori C}$, hosts a magnetic field significantly tilted with respect to the rotation axis, and that most of

the observed variability results from the interaction of the radiatively driven wind with the stellar magnetic field (as described in Babel & Montmerle 1997; Donati et al. 2002; ud-Doula & Owocki 2002; Townsend & Owocki 2005; Gagné et al. 2005). In this framework, the wind coming from each stellar hemisphere is deflected by the field towards the magnetic equator, where it produces a strong shock, an X-ray-emitting post-shock region (reaching temperatures of 10^7 K), and a cooler and denser disc in the magnetic equator where the wind plasma piles up before being ejected away from (or accreted back on to) the star. In a generic way, we can then ascribe the observed H α variations, in particular, to the varying aspect of the cool circumstellar disc; the emission attains a maximum strength when the disc is seen pole-on, and a minimum when the disc is seen edge-on. This could arise through recombination in a moderately optically thick disc.

With this assumption, the longitudinal field of HD 191612 should be maximum at maximum H α emission, i.e. at phase 0.50 in the ephemeris obtained by Walborn et al. (2004): JD_{min} = 244 8315 + 538E. Moreover, the strongly reduced H α emission observed around phase 0.0 indicates that the magnetic equator hosting the H α -emitting disc is seen close to edge-on in this viewing configuration. We therefore suggest that, as for θ^1 Ori C, the angle of the magnetic axis to the rotation axis β is close to $90^\circ - i$, where i is the angle of the rotation axis to the line of sight, to ensure that the magnetic equator is periodically seen edge-on (at phase 0.0) by the observer. Given the large amplitude of the H α variability, we can also conclude that neither i nor β is likely to be small.

For an initial, schematic, modelling attempt, we therefore propose for HD 191612 the simplest possible magnetic geometry, with $i = \beta = 45^\circ$ (as for θ^1 Ori C). In this context, the magnetic equator is seen edge-on at phase 0.0, and the magnetic pole is facing the observer at phase 0.5, in the Walborn et al. (2004) ephemeris. Our magnetic observations were taken at phase 0.725; by fitting the detected Zeeman signature to a magnetic dipole model, the single remaining free parameter of which is the field strength at the visible pole, we infer that the intensity of the dipole is -1.5 ± 0.2 kG.

An alternative is to imagine that the rotation period is actually twice 538 d, so that the magnetic poles rotate alternately into the line of sight. However, we consider this configuration to be unlikely. First, it would require β to be very close to 90° , so that the disc is viewed in the same orientation (and thus produces the same amount of H α emission) when each pole comes closest to the observer. Secondly, this option would produce edge-on disc viewing episodes that are much shorter than those obtained in the $\beta = 90^\circ - i$ case (where the disc approaches only asymptotically the edge-on configuration), in poor agreement with observations.

5 DISCUSSION

Several observational peculiarities of HD 191612 find a natural explanation in the framework of this model. For instance, Walborn et al. (2003) estimate that the mass loss of HD 191612 is about three times stronger at phase 0.5 (i.e. when the magnetic pole and associated open field lines face the observer) than at phase 0.0 (i.e. when the magnetic equator and associated closed field lines are seen edge-on). This is precisely what is expected in the context of a magnetically confined wind (see e.g. fig. 6 of Donati et al. 2002). Similarly, the shape of the *Hipparcos* light curve (Walborn et al. 2004) can be qualitatively explained by electron scattering in the disc, redirecting stellar photons to the observer at phase 0.5 and away from the line of sight at phase 0.0.

Since a rotation period of 538 d is rather long by O-star standards, it naturally raises the question of whether the magnetic field is responsible for angular momentum loss that produced the slow rotation. Focusing again on the very young star θ^1 Ori C suggests clues to answer this question. Since both stars have similar masses (of about $40 M_\odot$), HD 191612 can, to first order, be considered as an evolved version of θ^1 Ori C (the age of which does not exceed 0.2 Myr). In this evolution, the radius increases from about $8 R_\odot$ (for θ^1 Ori C: Howarth & Prinja 1989; Donati et al. 2002) to about $18 R_\odot$ (for HD 191612: Walborn et al. 2003) while the temperature decreases from about 45 000 K (Howarth & Prinja 1989; Donati et al. 2002) to about 35 000 K (Walborn et al. 2003); this is in rough agreement with evolutionary models of massive stars (e.g. Schaller et al. 1992; Claret 2004), from which we then derive an age of about 3–4 Myr for HD 191612. This is in good agreement with age estimates for the Cyg OB3 association (e.g. Massey, Johnson & Degioia-Eastwood 1995), of which HD 191612 is a member (Humphreys 1978).

This scenario would imply that HD 191612 hosted a field of about 15 kG when on the main sequence at an age similar to that of θ^1 Ori C today. However, the corresponding change in the moment of inertia (about a factor of 3, taking into account the simultaneous evolution of the fractional gyration radius k from 0.29 to 0.17: Claret 2004) does not of itself explain the change in rotation period between θ^1 Ori C (15 d) and HD 191612 (538 d, if our model is correct) by more than an order of magnitude.

To investigate whether the magnetic field may be responsible for the required angular momentum loss, we can evaluate the magnetic braking time-scale through the simple expression

$$t_A = k \frac{M_\star}{\dot{m}} \left(\frac{R_\star}{R_A} \right)^2, \quad (1)$$

where R_A is the Alfvén radius (i.e. the distance up to which the wind is magnetically confined) and \dot{m} is the *effective* mass-loss rate (determined by taking into account only the wind plasma that effectively leaves the star and thus contributes to angular momentum loss). To evaluate the effect of the magnetic field on the wind of HD 191612, it is useful to consider the wind magnetic confinement parameter η , defined by ud-Doula & Owocki (2002) and characterizing the ratio between the magnetic field energy density and the kinetic energy density of the wind:

$$\eta = B_{\text{eq}}^2 R_\star^2 / \dot{M} v_\infty, \quad (2)$$

where B_{eq} is the equatorial magnetic field, \dot{M} is the average mass-loss rate, and v_∞ is the terminal wind velocity. If η is significantly larger than 1, the magnetic field confines the wind within the Alfvén radius, which roughly scales as $\eta^{1/4}$ (ud-Doula & Owocki 2002).

While both HD 191612 and θ^1 Ori C have similar terminal wind velocities ($v_\infty \simeq 2500$ km s $^{-1}$), HD 191612 exhibits significantly stronger mass loss (by about an order of magnitude: Donati et al. 2002, Walborn et al. 2003). HD 191612 is also twice as large as, and features a $\sim 1.5\times$ stronger magnetic field than, θ^1 Ori C, implying that η is similar for both stars ($\eta \sim 10$), and thus that their Alfvén radii are roughly equal (at about $2R_\star$: Donati et al. 2002; Gagné et al. 2005). It also implies that the effective mass-loss rate of HD 191612, \dot{m} , corresponding to plasma evacuated through field lines opened by the wind (i.e. with a magnetic colatitude smaller than about 45°), is about 25 per cent of the actual surface mass flux, \dot{M} , or $\sim 1.5 \times 10^{-6} M_\odot \text{ yr}^{-1}$. Given the age of HD 191612, the magnetic braking time-scale that we derive, of the order of 1 Myr, indicates that the field of HD 191612 can, potentially, generate a

strong enough brake to have slowed the star down to the currently observed rotation rate.

One may argue that the angular momentum loss of HD 191612 may not have been as strong as now throughout its past life. While still on the main sequence with a radius and mass-loss rate comparable to those of θ^1 Ori C, HD 191612 would have had a magnetic field ~ 15 times larger than that of θ^1 Ori C, implying that its wind magnetic confinement parameter was about $\eta \simeq 5000$, and its Alfvén radius reached about $15R_*$ at that time. However, the correspondingly low effective mass-loss rate (of the order of $10^{-8} M_{\odot} \text{ yr}^{-1}$, or ~ 5 per cent of the total surface mass flux) would still have imposed rotational braking on a time-scale of the order of 1 Myr, the larger Alfvén radius roughly compensating for the smaller mass-loss rate. We therefore conclude that the angular momentum loss of HD 191612 did not drastically change throughout the life of the star, and that HD 191612 has had ample time to spin down since it was born.

This interpretation does not explain why θ^1 Ori C itself is apparently rotating more slowly than normal O stars; it is far too young for its magnetic wind to have influenced its rotation rate significantly. We speculate that, at some stage in its formation process, the magnetic interaction between the forming star and its accretion disc may have prevented the star from accumulating as much angular momentum as normal, weakly magnetic, hot stars, in a mechanism similar to that proposed for magnetic Ap stars (Stępień 2000). This speculation needs to be elaborated properly, however, and tested with adequate observations to see if it can realistically explain the slow rotation of newly born magnetic O stars.

Further spectropolarimetric observations of HD 191612, sampling the 538-d period of spectrum variability, are obviously needed to establish firmly whether this is indeed the rotation period of HD 191612; to put quantitative constraints on the magnetic field geometry of this newly discovered magnetic hot star; and to test the preliminary conclusions proposed in this paper. X-ray observations [such as those already undertaken by Nazé et al. (in preparation)] over the 538-d period will also help to constrain the magnetospheric physics and geometry, through the fluxes and spectral line shapes formed in the post-shock hot plasma torus, as well as from the periodic eclipses of the torus that the star may naturally provide (Babel & Montmerle 1997; Donati et al. 2002; Gagné et al. 2005).

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