Are the outflows in FU Orionis systems driven by the stellar magnetic field?

Arieh König1, Marina M. Romanova2 and Richard V. E. Lovelace2,3

1Department of Astronomy & Astrophysics and The Enrico Fermi Institute, The University of Chicago, Chicago IL 60637, USA
2Department of Astronomy, Cornell University, Ithaca, NY 14853, USA
3Department of Applied and Engineering Physics, Cornell University, Ithaca, NY 14853, USA

ABSTRACT

FU Orionis (FUOR) outbursts are major optical brightening episodes in low-mass protostars that evidently correspond to rapid mass-accretion events in the innermost region of a protostellar disc. The outbursts are accompanied by strong outflows, with the inferred mass outflow rates reaching $\sim 10\%$ of the mass inflow rates. Shu et al. proposed that the outflows represent accreted disc material that is driven centrifugally from the spun-up surface layers of the protostar by the stellar magnetic field. This model was critiqued by Calvet et al., who argued that it cannot reproduce the photospheric absorption-line shifts observed in the prototype object FU Ori. Calvet et al. proposed that the wind is launched, instead, from the surface of the disc on scales of a few stellar radii by a non-stellar magnetic field. In this paper we present results from numerical simulations of disc accretion on to a slowly rotating star with an aligned magnetic dipole moment that gives rise to a kilogauss-strength surface field. We demonstrate that, for parameters appropriate to FU Ori, such a system can develop a strong, collimated disc outflow of the type previously identified by Romanova et al. in simulations of protostars with low and moderate accretion rates. At the high accretion rate that characterizes the FUOR outburst phase, the radius $r_m$ at which the disc is truncated by the stellar magnetic field moves much closer to the stellar surface, but the basic properties of the outflow, which is launched from the vicinity of $r_m$ along opened-up stellar magnetic field lines, remain the same. These properties are distinct from those of the X-celerator (or the closely related X-wind) mechanism proposed by Shu et al. – in particular, the outflow is driven from the start by the magnetic pressure-gradient force, not centrifugally, and it is more strongly collimated. We show that the simulated outflow can in principle account for the main observed characteristics of FUOR winds, including the photospheric line shifts measured in FU Ori. A detailed radiative-transfer calculation is, however, required to confirm the latter result.

Key words: accretion, accretion discs – MHD – stars: formation – stars: magnetic field – stars: winds, outflows.

1 INTRODUCTION

FU Orionis systems (hereafter FUORs), named after their prototype object, are low-mass (Sun-like) protostars that undergo a rapid accretion episode in the innermost region of the circumstellar disc (see [Hartmann & Kenyon1996] for a review). The gravitational energy released in such an event leads to an emission outburst (with a rise time of $\sim 1 \sim 10$ yr and a duration of $\sim 10 \sim 100$ yr), during which the disc is more luminous than the central protostar by a factor of $\sim 10^2 \sim 10^3$. The inferred mass accretion rate during the outburst is $\dot{M}_{\text{in}} \approx 10^{-4} M_\odot \text{yr}^{-1}$, much higher than typical accretion rates during the quiescent phase. Statistical arguments, first advanced by [Herbig1977], indicate that such outbursts occur, on average, ten or more times during the protostellar lifetime. There is evidence that the outbursts are more frequent during the early (the so-called Class 0 and Class I) evolutionary phases and peter out as the mass accretion rate declines and the protostar enters the visible (Class II, or Classical T Tauri) phase. The picture that has emerged from the observations and their interpretation is that most of the mass that ends up in the protostar is transferred from the disc during such outbursts (e.g. [Calvet, Hartmann & Strom2000]).
flows and against a ‘stellar field’ scenario. They demonstrated that increasingly stronger photospheric lines observed in FU Ori become progressively more blueshifted even as their two absorption components (attributed to the disc rotation) move closer together in wavelength, and pointed out that this is precisely the behaviour expected in a disc-driven wind. In addition, based on the evidence that most of the optical continuum in FUORs is emitted by an extended disc and on the fact that typical stellar winds accelerate on scales comparable to the stellar radius, they contended that a stellar field-driven wind launched from the stellar surface could not reproduce the observations. In particular, they argued that the strong, but only moderately blueshifted, intermediate-strength lines detected in FU Ori could not originate in such a wind because, by the time such an outflow covered a significant fraction of the continuum emission region in the disc (necessary for producing strong absorption), it would have already attained a high velocity (and would therefore exhibit strongly blueshifted lines). Another potential problem that they cited involves the large rotational broadening that could be expected from a source rotating at breakup (as envisioned in the X-celerator picture).

Recent axisymmetric and 3D numerical simulations of disc accretion on to stellar magnetospheres (Romanova et al. 2009, hereafter R09) have revealed features that resemble the X-wind configuration proposed by Shu et al. (1994) but that are nevertheless different on several counts. Specifically, it was found that such systems drive conical disc winds along stellar field lines that are bunched up by the accretion flow. However, even though these winds also originate in the inner disc, their launching region is not confined to the immediate vicinity of the rotation radius, as hypothesized in the X-wind scenario. Furthermore, the conical winds are driven by the pressure gradient of the azimuthal magnetic field component (wound up by the differential rotation between the disc and the star) rather than centrifugally, and they have a smaller opening angle and a narrower lateral extent than X-winds. Interestingly, even though R09 only presented results for model parameters appropriate to protostars with comparatively low \(10^{-6} M_\odot \text{yr}^{-1}\) accretion rates, the outflows produced in their simulations exhibited several properties that could potentially mitigate the aforementioned arguments against stellar field-driven outflow models for FUORs. In particular, it was found that the acceleration of a conical wind is more extended than in a typical (hydrodynamic) stellar outflow and that its rotation speed generally decreases along the flow, in contrast with the initial behaviour of a centrifugally driven wind. These findings provide a strong motivation for reevaluating the viability of the ‘stellar field’ class of wind models for FUORs.

More recent investigations, employing larger simulation regions and higher accretion rates, have begun to extend the results of R09. One notable finding of this new work, analysed in Lii, Romanova & Lovelace (2011), is that the collimation of conical winds increases with distance from the origin and that they can eventually become fully collimated. In this paper we focus on simulations that we performed for parameters that are relevant to FUORs. Our goal is to verify that conical winds are still produced under these circumstances and to examine whether they could potentially account for the inferred properties of FUOR outflows. In Section 2 we provide analytic estimates that are used to guide our simulations and
we summarize our numerical scheme. In Section 2, we present representative results and derive the physical properties of the simulated flows. We discuss the implications of this study for FUORS in Section 3 and give our conclusions in Section 5, where we also outline steps toward further progress.

2 THE MODEL

The FUOR phenomenon has been convincingly argued to represent an enhanced accretion episode in a protostellar accretion disc, most likely associated with an instability that arises from a mismatch between the mass accretion rates in the inner and outer disc regions (e.g. Zhu, Hartmann & Gammie 2009a; Zhu et al. 2009b and references therein). Accordingly, we set up a numerical model that simulates a non-steady disc accretion ‘burst’ on to a magnetized star. We first discuss some basic scaling relations that allow us to choose the appropriate model parameters, and then briefly describe our numerical model.

2.1 Physical setup

Our model is based on the assumption that the stellar magnetic field can effectively diffuse into the inner region of the disc, allowing the bulk of the inflowing disc material to be channelled on to the stellar surface along closed magnetic field lines (e.g. Ghosh & Lamb 1979a,b) and the remainder to be expelled in an outflow along opened-up field lines (e.g. Lovelace, Romanova & Bisnovatyi-Kogan 1995; Goodson & Wingleee 1999). The disc truncation (or ‘magnetoospheric’) radius \( r_m \) corresponds to the location in the disc where the torque exerted on the disc plasma by the stellar magnetic field becomes large enough to brake the disc Keplerian rotation and enforce corotation with the star. For an aligned dipolar field, it is given by

\[
r_m = k_1 (GM_*)^{-1/7} \frac{M_\text{in}}{M_\text{in}} \frac{\mu_1}{\mu_1}^{4/7},
\]

where \( M_* \) is the stellar mass and \( \mu_1 \) is the magnetic dipole moment, \( G \) is the gravitational constant and the mass accretion rate is measured at \( r_m \) (Ghosh & Lamb 1979a). Under stationary conditions, the numerical factor \( k_1 \) is estimated to be \( \approx 0.5 \) (Ghosh & Lamb 1979b; Long, Romanova & Lovelace 2005). When \( r_m \) is close to \( R_* \), as in the FUOR case, higher order magnetic moments \( \mu_2 \), which produce magnetic field amplitudes \( B_n \sim \mu_n/r_n^{n+2} \), can also be expected to play a role. In this case, equation (1) generalizes to

\[
r_{m,n} = k_2 \mu_2^{4/(4n+3)} \frac{M_\text{in}}{M_\text{in}}^{-2/(4n+3)} (GM_*)^{-1/(4n+3)}
\]

(Long, Romanova & Lamb 2011), where, in particular, \( n = 1, 2 \) and \( 3 \) correspond, respectively, to the dipole, quadrupole and octupole field components. For a given dipole component, the incorporation of additional multipole components will tend to increase the value of the disc truncation radius over the estimate (1). However, for the sake of simplicity, we restrict the discussion in the rest of this paper to a purely dipolar field.

In choosing our model parameters, we adopt as fiducial values the physical parameters inferred from observations of FU Ori. In particular, based on the results given in Zhu et al. (2007), we take \( M_* = 0.3 M_\odot \) and \( M_\text{in} = 2.4 \times 10^{-4} M_\odot \) yr\(^{-1} \). These authors also estimate, from spectral modeling, that the inner radius \( r_in \) of the FU Ori disc is \( 5 R_\odot \). We identify this radius with \( r_m \), which allows us, using equation (1), to infer the value of \( r_m/R_* \):

\[
\frac{r_m}{R_*} = 1.20 k_1^{7/12} \left( \frac{M_*}{0.3 M_\odot} \right)^{-1/12} \left( \frac{B_n}{2 \text{kG}} \right)^{1/3} \times \left( \frac{r_m}{5 R_\odot} \right)^{5/12} \left( \frac{M_\text{in}}{2.4 \times 10^{-4} M_\odot} \right)^{-1/6},
\]

where the normalization of the equatorial surface magnetic field \( B_n = \mu_1/R_*^2 \) is consistent with typical values inferred in quiescent Class-I (Johns-Krull et al. 2009) and Class-II (e.g. Johns-Krull 2007) protostars as well as with the results reported by Donati et al. (2005) for the poloidal field near FU Ori. The contribution of higher order multipole field components, which could become important near the stellar surface, would have the effect of increasing this ratio.

Previous accretion disc models of FUORS have generally ignored the role of the magnetic field in truncating the disc and therefore identified \( r_m \), the inner radius of the disc, with the stellar radius (e.g. Zhu et al. 2005). The value \( R_* = 5 R_\odot \) inferred in this way is measurably higher than typical values for low-mass protostars (\( \leq 2.5 R_\odot \)), and several explanations have been advanced to account for the difference. (A brief summary of this issue is given by Zhu et al. 2007 who favour an interpretation that attributes the larger radius to stellar expansion brought about by the deposition of heat produced by the accreting gas.) Since \( r_m/R_* \) is generally \( \geq 1 \) in the magnetic accretion model (for example, it is 1.4 in the representative simulation presented in this paper), the inferred value of \( R_* \) is lower in this case, which reduces the implied difference from the radii of quiescent protostars.

2.2 Numerical setup

We employ the same numerical model as the one described in section 2 of R09, and the reader is referred to that paper for further details. As explained in section 2.3.1 of R09, the high-density gas that comprises the disc material enters the simulation region through the disc boundary only after the computation commences, and it subsequently flows inward on account of its viscosity. This numerical setup is thus naturally suited for modelling the evolution of an accretion ‘burst’, which is the focus of the present work.

Although we performed simulations for a variety of model parameters, we present only one representative case in this paper. We use the same parameters as in the reference simulation shown in R09, except that we reduce the reference radius \( R_0 \) from \( R_0 = 2 R_* \) to \( R_0 = R_* \) and change the outer radius of the computational domain from \( R_{\text{out}} = 16 R_0 \) to
The latter change enables us to increase the mass accretion rate on to the central star in our simulation to the level inferred in FUORs. The larger size of the computational domain also allows us to get a better handle on the collimation properties of conical winds. The mass accretion rate on to the central object is determined from the simulations using the expression

$$\dot{M}_{\text{simm}} = \dot{M}_{\text{in}} \dot{M}_0 = \tilde{\dot{M}}_{\text{in}} \left( \frac{\dot{M}_0}{\dot{M}} \right)^2 \frac{1}{(GM_*)^{1/2} R_0^{7/2}}$$,

where $\tilde{\dot{M}}_0$ is the reference mass accretion rate and where $\dot{M}$ and $\dot{M}_0$ are, respectively, the dimensionless magnetic moment and mass accretion rate parameters. We use $\dot{M} = 10$ as in the reference simulation of R09 and obtain the value of $\tilde{\dot{M}}_{\text{in}}$ from the numerical calculation. As described in Section 3, the final (quasi-steady) mass accretion rate on to the central object in our representative simulation corresponds to $\tilde{\dot{M}}_{\text{in}} \approx 70$. We also find that $r_{\text{in}}/R_\odot \approx 1.4$ at that stage, which implies $R_* \approx 3.6 R_\odot$ (using our fiducial value for $r_{\text{in}}$). We can then use equation (4) to infer the value of $B_r$ for our representative model:

$$B_r \approx 2.1 \left( \frac{M_*}{0.3 M_\odot} \right)^{1/4} \left( \frac{\dot{M}}{2.4 \times 10^{-4} M_\odot \text{yr}^{-1}} \right)^{1/2} \left( \frac{R_*}{3.6 R_\odot} \right)^{-5/4} \text{kG}.$$ (5)

The reference and fiducial parameters for our model are summarized in Table 1.

The time evolution of the simulated system depends on the magnitudes of the viscosity and the magnetic diffusivity, which are parameterized by $\alpha_v$ and $\alpha_d$, respectively. R09 (see their appendix D) found that conical winds are established only when $\alpha_v \gtrsim \alpha_d$. This is consistent with the fact that the dragging of the magnetic field by the accretion flow, which in FUORs causes the field compression near the inner boundary of the disc, requires the magnetic Prandtl number $\tilde{\nu}_m = \alpha_v/\alpha_d$ to be $\gtrsim 1$ (e.g. Lubow, Papaloizou & Pringle 1994). Our simulations employ the values adopted in the reference case of R09, namely $\alpha_v = 0.3$ and $\alpha_d = 0.1$. Recent work on non-steady protostellar accretion-disc models (e.g. Zhu et al. 2009a,b, 2010) has indicated that $\alpha_v$ must be large enough ($\gtrsim 0.1$) for outbursts that resemble those of FUORs to be produced. Our adopted value of the viscosity parameter is consistent with this requirement. It is noteworthy in this connection that R09 found that the formation of a robust conical outflow also requires $\alpha_v$ (and $\alpha_d$) to be comparatively large ($\gtrsim 0.03$).

### 3 Simulation Results

The large-scale poloidal structure of the simulated flow is shown in Fig. 1 at the time when the wind has become fully developed. The most striking feature of the figure is its qualitative similarity to fig. 3 in R09, which corresponds to a quiescent protostar that accretes at a much lower (by a factor $\sim 3 \times 10^{-3}$) rate. This conclusion is reinforced by an inspection of Fig. 2, which shows a close-up view of the region near the star. In both cases a high-density, conical disc wind is launched from the vicinity of the disc truncation radius $r_{\text{in}}$, and a lower-density, higher-velocity jet component is established in the interior of the cone. The main difference between the two simulations is in the value of $r_{\text{in}}/R_\odot$: it is $\sim 1.4$ in our simulation, as compared with $\sim 2$ in the R09 reference calculation. This difference is consistent with the expectation from equation (3), which indicates that this ratio scales only as a weak power of the mass accretion rate ($\dot{M}_*^{-1/6}$). Thus, even though the accretion flow is much more powerful in this case, the steep radial scaling of the magnetic pressure exerted by the dipolar field component ($\times r^{-6}$) insures that the disc is still truncated at a finite radius and does not actually ‘crush’ the stellar magnetosphere (as envisioned, for example, in the X-celerator scenario for FUORs; see Zhu et al. 1994).

Although the disc in the current simulation is truncated very close to the stellar surface, the magnetic field structure in the vicinity of its inner radius is qualitatively very similar to the case where $(r_{\text{in}} - R_\odot)/R_\odot$ is $\gtrsim 1$. In particular, the magnetic field lines that guide the conical wind and the axial jet are open. The opening-up of parts of the initially dipolar stellar field is a consequence of the differential rotation between the star, where the magnetic field is anchored, and the disc, into which the field lines diffuse, and is a generic property of magnetically linked star-disc systems (e.g. van Ballegooijen 1994; Lynden-Bell & Boily 1994; Lovelace et al. 1995; Uzdensky, Königl & Litwin 2002). As in the lower-$M_\odot$ case considered in R09, the conical wind is driven primarily by the pressure gradient of the azimuthal magnetic field component generated by the differential rotation rather than centrifugally. Note in this connection that the profile of the azimuthal velocity component (see panel C in fig. 6 of R09 as well as the right panel of Fig. 2 below) initially decreases along the poloidal field lines, which contrasts with the behaviour of centrifugally driven winds, in which the azimuthal speed $v_\phi$ at first increases along a field line. The acceleration is quite efficient, and the conical wind reaches outflow speeds $v_\phi \approx 80 - 90 \text{ km s}^{-1}$ (corresponding to $\sim 75 - 84\%$ of the Keplerian speed at $r_{\text{in}}$) at the outer edge of the simulation region. The highest poloidal speed observed in this simulation is attained further up and is associated with the lower-density axial flow. As seen in Fig. 1 its value is $\sim 300 \text{ km s}^{-1}$, which is consistent with the maximum line-of-sight speed measured in FU Ori (Bastian & Mundt 1985). However, this value may not be accurate since the low-density region in the vicinity of the axis is susceptible to numerical artifacts. Near the base
Table 1. Reference values (subscript ‘0’) and fiducial values used in the representative model. See Section 2.2 and section 2.2 in R09 for further details.

|                | FU Ori |
|----------------|--------|
| $M_*$ ($M_\odot$) | 0.3    |
| $R_*$ ($R_\odot$) | 3.6    |
| $R_0$           | $R_*$  |
| $v_0$ (cm s$^{-1}$) | $1.3 \times 10^7$ |
| $P_*$ (days)    | 7.4    |
| $P_0$ (days)    | 1.4    |
| $B_*$ (G)       | $2.1 \times 10^3$ |
| $B_0$ (G)       | 210.0  |
| $\rho_0$ (g cm$^{-3}$) | $2.8 \times 10^{-10}$ |
| $\dot{M}_0$ ($M_\odot$ yr$^{-1}$) | $3.4 \times 10^{-6}$ |
| $N_0$ (dyne cm) | $7.0 \times 10^{38}$ |

Figure 1. Poloidal matter flux $\rho v_p$ (in color, with the scale given at the bottom), sample poloidal magnetic field lines (yellow) and poloidal velocity vectors (red) for the representative conical-wind model at time $T \approx 1290$ d after the onset of the simulation, when the flow configuration in the innermost region is already fully developed.

of the flow the wind velocity is dominated by the azimuthal component, which arises from the rotational motion of the disc in the wind-launching region and has a maximum value of $\sim 106$ km s$^{-1}$, attained at $r \approx r_{in}$. (At smaller radii the wind azimuthal velocity decreases on account of the interaction with the magnetosphere, which rotates with the comparatively low angular velocity of the star.) We note that, even though the wind is launched very close to the stellar surface and has a high initial rotation velocity, it does not originate in the stellar surface and does not require the star to rotate at break-up speed – which distinguishes it from the outflow envisioned in the X-celerator scenario (Shu et al. 1988).

As discussed in R09, the magnetic force also has a component directed toward the symmetry axis, which acts to collimate the wind. By using the poloidal matter flux distribution, R09 determined that the conical outflow in their reference simulation attained an opening half-angle of $\sim 30^\circ - 40^\circ$.

From the corresponding distribution presented in Fig. 1, we
find that the collimation is even more efficient in the case that we simulate, with the outflow half-angle decreasing to \(\lesssim 10^\circ\) within a radial distance (projected on the equatorial plane) of \(\lesssim 4 R_\star\) from the stellar surface. In general, a magnetically driven outflow is collimated by a combination of two effects (e.g., Blandford & Payne 1982): the magnetic tension force that acts to balance the magnetic pressure-gradient force in the force-free sub-Alfvénic regime, and the hoop stress exerted by the azimuthal magnetic field component in the super-Alfvénic flow region.\(^8\) The difference in the collimation properties of the conical wind in our simulation and in the reference simulation of R09 can be attributed to the fact that a higher mass accretion rate in the disc results in a stronger compression of the stellar magnetic field and hence in a larger collimating magnetic tension force in the sub-Alfvénic region of the wind. The hoop-stress effect is also stronger in the higher-\(M_{\text{in}}\) case on account of the compressional amplification of the field and because the differential rotation that twists the field lines gets stronger (for a given value of \(r_{\text{cor}}\)) as \(r_{\text{in}}\) is decreased. A detailed analysis of the collimation properties of a conical wind from a high-\(M_{\text{in}}\) disc is given in Lii et al. (2011).

Fig. 3 shows the evolution of the matter fluxes that are deposited by the accretion flow on to the stellar surface and in the outflow (with the mass outflow rate evaluated over a spherical surface far enough from the centre). It is seen that the mean mass accretion rate increases steadily until it attains a fully developed state (with \(M_{\text{in}}\) corresponding to the value inferred in FU Ori) at a time \(T \approx 1130\) d from the start of the simulation. This time is longer than the \(\sim 1\) yr observed rise time of the FU Ori outburst (e.g., Hartmann & Kenyon 1996, but the discrepancy is probably in large part just a consequence of the particular choice of initial conditions for our simulation (see Section 2.2). In the fully developed state, the average accretion and outflow rates are related by \(M_{\text{out}}/M_{\text{in}} \approx 0.13\). This result is consistent with the observational findings in FU Ori (e.g., Croswell et al. 1987).

The rapid accretion during the FUOR outburst can be expected to spin up the star, and it is therefore necessary to check whether our assumption of slow stellar rotation is self-consistent. We calculated the torque on the star at the end of our simulation from the expression \(N = (N_T + N_N)n_0\), where the reference torque \(N_0 = M_{\text{out}}R_0\) is listed in Table 1 and where the dimensionless field and matter contributions \(N_T\) and \(N_N\) are, in our case, \(\simeq 28\) and \(\simeq 23\), respectively.\(^9\) By dividing the total torque calculated in this way, \(N \approx 3.6 \times 10^{28}\) dyne cm, into the stellar angular momentum \(J_\star = k^2M_\star R_\star^2\Omega_\star \approx 7.3 \times 10^{29}(k^2/0.2)\) g cm\(^2\) s\(^{-1}\), where we assume uniform rotation with angular velocity \(\Omega_\star = (GM_\star/r_{\text{cor}}^3)^{1/2}\) and scale the normalized radius of gyration \(k^2\) by its value for a polytropic of index 1.5, we infer a characteristic spin-up time \(\sim 65\) (\(k^2/0.2\)) yr, which is of the order of the typical FUOR outburst time. This implies that our assumption of a slow rotator is only marginally consistent. We note, however, that a conical wind-like component may be present in the outflow even if this assumption is violated (see Section 5).

4 IMPLICATIONS FOR FUOR OUTFLOWS

The simulation results presented in Section 3 indicate that the observed properties of FUOR outflows could in principle be explained in terms of the conical wind and axial jet that are driven from the vicinity of the stellar surface in these systems along stellar magnetic field lines that are compressed, twisted, and opened up by the interaction between the initially dipolar field component and the strong accretion flow. In particular, for typical values of the stellar mass, radius and surface magnetic field strength, and of the mass inflow rate at the inner edge of the circumstellar disc, our representative simulation demonstrates that this interaction can produce outflows whose properties (mass outflow rate, strong rotational velocity component near the base and possibly also the maximum outflow speed) are consistent with the observations.

As was mentioned in Section 1 CHK93 and Hartmann & Calvet (1995) argued against a stellar magnetic field-driven wind being able to account for the spectral properties of the outflow in FU Ori. They envisioned the outflow as originating in the stellar surface and accelerating rapidly along strongly divergent field lines even as its rotation speed (which initially has the stellar breakup value) continues to increase. In our picture, the absorption features modelled in the above-mentioned papers would arise in the conical-wind component, which exhibits a spatially more extended acceleration (along fast collimating magnetic field lines) and a lower initial rotation speed (that at first actually decreases along the flow) than the ‘stellar field’ outflow assumed in those papers. Although the spatial and kinematic properties of our simulated conical wind are distinct from the semi-analytic disc outflow model presented in CHK93 (which combined a hydrostatic disc atmosphere with a simple representation of a centrifugal wind), it is probably qualitatively closer to that model (which CHK93 and Hartmann & Calvet 1995 argued was consistent with the spectral data for FU Ori) than to their hypothesized stellar wind model.

To demonstrate that the conical wind model could account for the behaviour of the absorption lines measured in FU Ori would require a determination of the thermal structure of the simulated flow and a calculation of the synthesized spectra of the relevant photospheric lines. An analogous radiative-transfer calculation, addressing the rotationally induced line variability from an accreting T Tauri star with a misaligned magnetic dipole, was carried out by Kurosawa, Romanova & Harries (2008). While a detailed computation of this type is outside the scope of the present paper, we can obtain some indication of the potential promise of this model by calculating the density and velocity profiles as functions of distance from the mid-plane at the location of the optical continuum emission region and comparing the results with those obtained in the disc wind model of CHK93. In view of the
Figure 2. Innermost region of the simulation domain presented in Fig. 1, showing details of the disc–star interaction and the formation of a conical wind. The inner radius of the disc is denoted by $r_{in}$. The arrows depict poloidal velocity vectors, whereas the black lines represent sample poloidal magnetic field lines. The white line labelled $\beta = 1$ marks the surface where the gas pressure $p$ is equal to the magnetic pressure $B^2/8\pi$. The heavy dash-dotted line that starts at $r = 2r_{in}$ marks the trajectory along which the conical wind parameters are plotted in Fig. 4.

Figure 3. Time evolution of the matter discharges from the disc on to the star (top curve) and into the wind (bottom curve). The mass outflow rate is calculated by integrating the matter flux over a spherical surface of radius $R = 6 R_*$. 
clear differences between our numerical model and CHK93’s semi-analytic model (which include the fact that the latter model, in contrast with our simulations, incorporates energy loss by radiative diffusion in the disc atmosphere), we cannot expect to find a full quantitative correspondence between the two calculations. However, we can look for common trends in the respective profiles. We take the optical emission radius \( r_{\text{opt}} \) to correspond to an effective disc temperature of 5300 K, and we use the disc model of Zhu et al. (2007), in which \( T_{\text{eff}}(r) \propto (r_{\text{in}}/r)^{\alpha} [1 - (r_{\text{in}}/r)^{\beta}] \) and the maximum effective temperature (attained at \( r_{\text{max}} \approx 1.36 \times 10^{-2} \) for \( T_{\text{max}} = 6420 \) K, to deduce \( r_{\text{opt}} = 2.37 \times 10^{-2} \). As noted by CHK93, the disc model fits of Kenyon, Hartmann & Hewett (1988) similarly imply that roughly 60% of the optical spectrum in FU Ori arises from disc annuli between 1.5 \( r_{\text{in}} \) and 3 \( r_{\text{in}} \). CHK93 suggested that this region could be adequately represented by their calculated ‘disc atmosphere plus wind’ structure at \( r = 2 \times 10^{-2} \) which they presented as a function of the height \( z \) above the mid-plane in their table 2. In view of the different model setups and adopted source parameters, there are several possible choices for the value of the wind-launching distance from the origin, \( r \), and we use the data in table 2 of CHK93. In view of the conical shape of our simulated wind, we plot the poloidal and azimuthal components as well as the density in the numerical model along a slightly inclined path (represented by the heavy dash-dotted straight line in Fig. 2). It is seen that, as expected, the values of corresponding quantities at a given distance from the mid-plane can be significantly different for the two cases. However, we also find that the basic velocity and density structure of the two models is very similar. In both cases, the flow is rotation-dominated as it emerges from the disc but eventually \( v_p \) comes to exceed \( v_\phi \) (which, in turn, does not systematically increase along the flow). CHK93 estimated that the disc photosphere at \( r = 2 \times 10^{-2} \) occurs roughly where the density drops to \( \sim 10^{-9} \, \text{g cm}^{-3} \) and \( v_p \) increases to \( \sim 1 \, \text{km s}^{-1} \). (For comparison, the sound speed in the optical emission region is \( \sim 5 \, \text{km s}^{-1} \)). In their model, \( v_p \) becomes \( \geq v_\phi \) when the density drops to \( \sim 10^{-11} \, \text{g cm}^{-3} \). In our simulation, \( v_p \) increases above \( \sim 1 \, \text{km s}^{-1} \) also roughly when the density drops to \( \sim 10^{-9} \, \text{g cm}^{-3} \), and \( v_p \) comes to exceed \( v_\phi \) when \( \rho \) decreases by another two orders of magnitude. This correspondence indicates that the observed dependence of photospheric absorption line profiles in FU Ori on the line strength, which was successfully reproduced by the CHK93 model (see also Hartmann & Calvet 1995), is consistent with an origin in a stellar field-driven conical wind.

Even if more extensive and detailed calculations indicate that the observed behaviour of the photospheric absorption lines in FU Ori cannot be reproduced by a conical wind model (because, for example, a wind of this type that is launched very close to the surface collimates too rapidly for its acceleration region to intercept a line of sight to the optical continuum emission region for the inferred disc inclination angle, or if the maximum predicted outflow speed is too low), the results of our simulations suggest that a stellar field-driven outflow might still be an important ingredient of a comprehensive model of FUORs. In particular, such an outflow could still potentially account for much of the mass and momentum injected into the ambient medium in the course of an outburst and perhaps also for the highest measured velocities in the H\( \alpha \), H\( \beta \) and Na I lines (e.g. Bastian & Mundt 1985; Hartmann & Calvet 1995; even if another outflow component (in particular, a disc wind driven along non-stellar magnetic field lines, which were not included in our simulations) gives rise to the observed photospheric lines. This is because a strong conical wind and a fast, low-density jet appear to be generic features of the disc/stellar-field interaction under a wide range of conditions. On the other hand, if it can be demonstrated that these predicted outflow components are, in fact, absent during FUOR outbursts, this would indicate that at least one of the underlying key assumptions of the model (e.g. that the magnetic diffusivity in the inner disc does not exceed the viscosity (\( \alpha_d \lesssim \alpha \)), but is nevertheless sufficiently large (\( \alpha_d \gtrsim 0.03 \)), or that the star possesses a sufficiently strong dipolar field component (\( \mu \gtrsim 3 \times 10^{27} \, \text{G cm}^{-3} \)) is not valid, which would also enhance our physical understanding of these systems.

5 CONCLUSION

We have presented numerical simulation results that support an interpretation of the powerful winds that accompany FUOR outbursts in terms of stellar magnetic field-driven disc outflows. In this picture, the massive accretion flow that gives rise to an observed burst strongly compresses the stellar magnetic field lines, and the resulting magnetic stress truncates the accretion disc very close to the stellar surface. Some of the field lines diffuse into the disc and become twisted by the differential rotation between the disc and the star. This twisting, in turn, opens up the field lines, and the pressure gradient associated with the azimuthal magnetic field component along the opened field drives a moderate-velocity, dense conical wind that emanates from the vicinity of the trunca-
Magnetic driving of FU Orionis outflows

Figure 4. Variation of the density (left panel) and of the poloidal and azimuthal velocity components (right panel) of the conical wind along the ray marked by a heavy dash-dotted straight line in Fig. 2. These quantities are depicted by solid lines, starting at the location where $v_p$ first increases above $1 \text{ km s}^{-1}$. The dashed line continues the $v_p$ curve along the same path to lower elevations, where the disc rotates at the local Keplerian speed. Also shown are the variations of $\rho$ and $v_z$ along a strictly vertical line segment in the CHK93 semi-analytic disc-wind model for FU Ori (subscript ’CHK’). In the latter model, the azimuthal velocity is assumed to be constant with height and is equal to $103 \text{ km s}^{-1}$. In both cases, the outflow is launched at $r = 2 r_\text{m}$. However, because of differences in the adopted source parameters, the physical radial scale corresponding to this value is $10.00 R_\odot$ and $8.84 R_\odot$, respectively, in the numerical and semi-analytic models.

The conical wind and axial jet appear to be generic features of the interaction between an accretion disc and a predominantly dipolar stellar field in cases where the effective viscosity $\alpha_v$ and magnetic diffusivity $\alpha_d$ satisfy $\alpha_v \gtrsim \alpha_d$ and are both comparatively high ($\gtrsim 0.03$). These features were originally identified in simulations of protostars with low and moderate accretion rates (R09). The representative simulation presented in this paper verifies that the same type of outflow is produced also when the accretion rate is as high as $\sim 2.4 \times 10^{-4} M_\odot \text{ yr}^{-1}$, the value inferred in the archetypal object FU Ori. Our simulation implies that the disc truncation radius in this source, which was observationally determined to lie at a radius $r_\text{m} = 5 R_\odot$, corresponds to a distance of $0.4 R_* \approx 1.4 R_\odot$ from the stellar surface, and that the surface magnetic field is $\sim 2.1 \text{ kG}$, which is consistent with independent indications. The mass outflow rate in the simulated outburst (dominated by the conical wind) is a factor $\sim 0.1$ of the mass accretion rate on to the star, and the maximum outflow velocity within the computational domain (attained in the axial jet) is $\sim 300 \text{ km s}^{-1}$; these agree well with the observationally inferred values for FU Ori.

An interpretation of FUOR winds in terms of an accretion-disc outflow driven along stellar magnetic field lines was previously proposed by Shu et al. (1994) on the basis of the X-celerator model of Shu et al. (1988). In this picture, the outflow is launched centrifugally from the surface of a star whose outer layers rotate at breakup speeds. This contrasts with the conical-wind scenario, in which the star rotates comparatively slowly and the outflow originates at a finite distance from the star and is driven by the $B_\phi$ magnetic pressure gradient from the start. Shu et al. (1994) generalized the X-celerator model to the case where the star rotates below breakup, corresponding to the corotation radius $r_\text{cor}$ exceeding $R_*$. However, in their generalized (X-wind) model, $r_\text{cor}$ still coincides with the magnetospheric radius $r_\text{m}$, and the nature of the outflow from that region (the X-point) is qualitatively similar to that of the X-celerator model. Our assumption in this paper that $r_\text{m} < r_\text{cor}$ is plausible in view of the fact that a rapidly rotating protostar could be efficiently braked through a magnetic interaction with the disc during the relatively long quiescent phase (e.g. Königl 1991; Ustyugova et al. 2006). And while such a star would be spun up during the rapid accretion event comprising an FUOR outburst (see Section 3), this need not result in the surface layers reaching breakup speeds. (Note in this connection that, even in the absence of a large-scale magnetic field coupling the disc and the star, the protostellar surface layers are not expected to reach breakup speeds during an outburst of this type; e.g. Popham et al. 1993, 1996).

CHK93 and Hartmann & Calvet (1995) argued that a stellar magnetic field-driven outflow model of the X-celerator type is inconsistent with the detection of moderately blueshifted, intermediate-strength absorption lines in FU Ori, which, they suggested, could be explained in terms of a disc outflow originating at a distance $r$ of a few stellar radii and driven along magnetic field lines that are not associated with the star. Specifically, they showed that the observed line profiles could be reproduced by a model in which gas launched from a Keplerian accretion disc gradually accelerates until the poloidal velocity component comes to exceed the azimuthal velocity component. In this paper we have demonstrated that a conical wind naturally exhibits this behaviour since the outflow also starts with a predominantly azimuthal velocity component and eventually accelerates to $v_p > v_\phi$. In particular, we showed that the density and poloidal velocity profiles along a ray through the conical shell that intersects the disc at
the distance of the optical emission region closely match the corresponding profiles calculated in the disc-outflow model of CHK93, notwithstanding the different setups (and even the fiducial parameter values) employed in the two (respectively, numerical and semi-analytic) models. The fact that the azimuthal velocity of the conical wind remains much lower than the breakup speed of the star and that, in contrast with the initial behaviour of $v_\phi$ in a centrifugally driven wind, it does not increase (but, rather, decreases) along the outflow, circumvents another objection that CHK93 levelled at the X-celerator scenario. We note in this connection that an outflow component resembling a conical wind, as well as a strong axial jet component, have been found in simulations of the disc–magnetosphere interaction in the ‘propeller’ regime ($r_{\text{in}} > r_{\text{cor}}$). Based on the results presented in R09, we expect such a flow to be more strongly influenced by the centrifugal force and less well collimated for given values of $\mu_1$ and $M_{\text{in}}$ than the conical wind we considered above. However, R09 also found in the propeller case that the magnetic force remains important in driving the wind and that the azimuthal speed of the wind does not increase along a field line (see their fig. 11). It is therefore conceivable that an outflow in this regime could also account for the observations, although this remains to be verified by an explicit simulation.

While the results presented in this paper are highly suggestive, a more detailed calculation (involving the thermal and spectral properties of the outflow) is required to evaluate the contribution of a stellar field-driven disc wind to the absorption-line spectrum in an object like FU Ori. It will also be useful to carry out additional simulations in order to further check the dependence of the results on the adopted initial mass and magnetic flux distributions. In particular, our assumption that initially there is no disc (as compared to coronal gas in the simulation region) is unrealistic, and our current numerical setup also does not account for the possibility that some of the stellar magnetic field may have diffused into the disc before the onset of the outburst (see Goodson & Winglee 1999). Given the comparatively high value of the disc inclination angle ($i = 55^\circ$; Malbet et al. 2005) adopted in recent studies of FU Ori, it is conceivable that the conical wind model would not be able to reproduce the absorption-line profiles measured in this object if the source of the optical continuum is indeed a region of size $r_{\text{opt}} \gtrsim 2 r_{\text{in}} = 10 R_\odot$ in the disc. In that case a disc outflow driven along a non-stellar magnetic field, as proposed by CHK93, might provide the dominant contribution to the absorption-line spectrum of FU Ori, although a ‘conical wind plus axial jet’ outflow could potentially still contribute to some of the observed properties of this object. Note, however, that if a stellar wind is also present (see section 5.2 of R09), it would have a decollimating effect on the conical wind (e.g. Meliani, Casse & Sauty 2006, Fendt 2009) that could increase the range of disc radii ‘covered’ by the conical outflow.

To our knowledge, photospheric line shifts such as those detected in FU Ori have so far not been found in any other FUOR. Although a lower-$M_{\text{out}}$ wind or some other factor (such as a higher projected azimuthal velocity) could have prevented a detection in other FUORS (see Hartman & Calvet 1995), it would clearly be useful to be able to test competing models also in other bursting sources. Lower-amplitude, repetitive photometric outbursts have been detected in EX Lupi and a few other T Tauri stars (e.g. Herbig 1989, 2008), and they have also been interpreted as enhanced mass accretion events. In a few of these EXOR sources there is evidence for an accompanying outflow, which, as discussed in R09, may well (at least in some cases) arise in a disc–magnetosphere interaction. However, these systems generally do not exhibit absorption-line spectra like FUORs, and there is also no indication that their continuum emission is dominated by a disc; in this regard their appearance is similar to that of quiescent systems. Therefore, unless other spectroscopic diagnostics are identified in these sources, FUORs will remain the best candidates for probing the acceleration regions of protostellar disc outflows.

ACKNOWLEDGMENTS

This research was supported in part by NSF grants AST-0908184 (AK) and AST-1008636 (MMR and RVEL) and by a NASA ATP grant NNX10AF63G (MMR and RVEL). The authors thank G. V. Ustyugova and A. V. Koldoba for the development of the code used in the simulations discussed in this paper, and the reviewer for comments that helped to improve the presentation.

REFERENCES

Bastian U., Mundt R., 1985, A&A, 144, 57
Blandford R. D., Payne D. G., 1982, MNRAS, 199, 883
Calvet N., Hartmann L., Kenyon S. J., 1993, ApJ, 402, 623 (CHK93)
Calvet N., Hartmann L., Strom S. E., 2000, in Mannings V. G., Boss A. P., Russell S., eds, Protostars & Planets IV. Univ. Arizona Press, Tucson, p. 377
Clarke C. J., Lin D. N. C., Pringle J. E., 1990, MNRAS, 242, 439
Croswell K., Hartmann L., Avrett E. H., 1987, ApJ, 312, 227
Donati J. F., et al., 2007, MNRAS, 380, 1297
Donati J. F., et al., 2008, MNRAS, 386, 1234
Donati J. F., Paletou F., Bouvier J., Ferreira J., 2005, Nature, 438, 466
Fendt C., 2009, ApJ, 692, 346
Hartmann L., Calvet N., 2005, MNRAS, 360, 1297
Herbig G. H., 1977, ApJ, 217, 693
Herbig G. H., 1989, in Reipurth, B., ed, ESO Workshop on Low-Mass Star Formation and Pre–Main-Sequence Objects. ESO, Garching, p. 233
Herbig G. H., 2007, AJ, 133, 2679
Herbig G. H., 2008, ApJ, 135, 637
Herbig G. H., Petrov P. P., Duemmier R., 2003, ApJ, 595, 384
Hartman L., Kenyon S. J., 2003, ApJ, 135, 111
Hartmann L., Calvet N., 1995, AJ, 109, 1846
Hartmann L., Kenyon S. J., 1996, ARA&A, 34, 207
Kurosawa M., Romanova M. M., Harries T. J., 2008, MNRAS, 385, 1931
Magnetic driving of FU Orionis outflows

Lii P., Romanova M. M., Lovelace R. V. E., 2011, MNRAS, submitted (arXiv:1104.4374)
Long M., Romanova M. M., Kulkarni A. K., Donati J. F., 2011, MNRAS, 413, 1061
Long M., Romanova M. M., Lamb F. K., 2011, New Astronomy, submitted (arXiv:0911.5455)
Long M., Romanova M. M., Lovelace R. V. E., 2005, ApJ, 634, 1214
Lovelace R. V. E., Romanova M. M., Bisnovatyi-Kogan G. S., 1995, MNRAS, 275, 244
Lubow S. H., Papaloizou J. C. B., Pringle, J. E., 1994, MNRAS, 267, 235
Lynden-Bell D., Boily C., 1994, MNRAS, 267, 146
Malbet F., et al., 2005, A&A, 437, 627
Meliani Z., Casse F., Sauty C., 2006, A&A, 460, 1
Popham R., Kenyon S., Hartmann L., Narayan R., 1993, ApJ, 473, 422
Popham R., Narayan R., Hartmann L., Kenyon S., 1993, ApJ, 415, L127
Reipurth B., 1990, in Mirzoyan, L. V., Pettersen B. R., Tsvetkov M. K., eds, Proc. IAU Symp. 137, Kluwer, Dordrecht, p. 229
Romanova M. M., Long M., Lamb F. K., Kulkarni A. K., Donati J.-F., 2011, MNRAS, 411, 915
Romanova M. M., Ustyugova G. V., Koldoba A. V., Lovelace, R. V. E., 2009, MNRAS, 399, 1802 (R09)
Shu, F. H., Lizano S., Ruden S. P., Najita J., 1988, ApJ, 328, L19
Shu, F. Najita J., Ostriker E., Wilkin F., Ruden S., Lizano S., 1994, ApJ, 429, 781
Skinner S. L., Sokal K. R., Güdel M., Briggs K. R., 2009, ApJ, 696, 766
Ustyugova G. V., Koldoba A. V., Romanova M. M., Lovelace R. V. E., 2006, ApJ, 646, 304
Uzdensky D., Königl A., Litwin C., 2002, ApJ, 565, 1191
van Ballegooijen A. A., 1994, SSRv, 68, 299
Zhu Z., Hartmann L., Calvet N., Hernandez J., 2007, ApJ, 669, 483
Zhu Z., Hartmann L., Calvet N., Hernandez J., Tannirkulam A.-J., D'Alessio P., 2008, ApJ, 684, 1281
Zhu Z., Hartmann L., Gammie, C., 2009a, ApJ, 694, 1045
Zhu Z., Hartmann L., Gammie C., Book L. C., Simon J. B., Engelhard E., 2010, ApJ, 713, 1134
Zhu Z., Hartmann L., Gammie C., McKinney, J. C., 2009b, ApJ, 701, 620