THE INTERNAL STRUCTURE OF A NON-RELATIVISTIC JET.

V. S. Beskin, *P. N. Lebedev Institute of Physics, RAS, 53 Leninsky pr., 119991 Moscow, Russia, (beskin@lpi.ru)*, E. E. Nokhrina, *Moscow Institute of Physics and Technology, 9 Insitutsky per., 141700, Dolgoprudny, Russia, (nokhrinaelena@gmai.com)*.

Introduction. The young stellar objects (YSOs) — pre-main sequence stars that are still in their accretion phase — are mainly accompanied by the parsec-scale collimated jets (the Herbig-Haro (HH) objects). These jets are the natural outlet of the excess angular momentum of accreting matter. The most attractive explanation for such a highly collimated outflows launched from the star-disk system is the magneto-hydrodynamical (MHD) models. The latest high-resolution observations indicating the jet rotation [1,2] supports this idea. The systematic asymmetries in Doppler shift across the jet are explained by the presence of regular toroidal velocities of the order of $10-30$ km/s, while the bulk velocity of high velocity component (HVC) of a jet is usually estimated to be $100-300$ km/s.

We present the MHD model of an already collimated non-relativistic jet (which we are modelling as one-dimensional outflow for simplicity) observed in YSOs. We suggest that a jet collimation is due to a finite gas and/or magnetic pressure of outer media. Indeed, the simplest consideration of the magnetic flux conservation gives us the correct jet radius for YSOs. Proposing that it is the external magnetic field $B_{ext} \sim 10^{-6}$ G that plays the main role in the collimation, we can write down

$$r_{jet} \sim R_{in} \left(\frac{B_{in}}{B_{ext}}\right)^{1/2}, \qquad (1)$$

where R_{in} and B_{in} are the radius and the magnetic field of the compact object respectively. The similar evaluation for the jet dimension can be obtained if we propose the external pressure $P_{ext} \sim B_{ext}^2/8\pi$. As for YSOs $B_{in} \sim 10^2 - 10^3$ G, and $R_{in} \sim R_{\odot}$, we obtain $r_{jet} \sim 10^{15}$ cm in agreement with observational data. It means that the external media may indeed play important role in the collimation process [3,4,5,6,7].

It turns out that even regard of such an already collimated jet puts some restrictions on the outflow properties near the origin. In particular, we show in this work that the thermal effects are very important and can not be omitted. Although we do not consider the collimation process itself due to the complicatedness of such a problem, we propose that an oblique shock must stand while the flow is collimated. Such a shock is needed for constructing the collimated jet and seems inevitable in our model. It is well known that such a shock is needed to explain the emission line profiles observed in HH [8,9].

The problem statement. We use the following model to construct a jet structure in the far region (the details are given below): the initially monopole-like outflow formed by the magnetic field of a star propagates outward. It crosses the critical surfaces (slow magnetosonic, Alfvénic, and fast magnetosonic) while the pressure of a magnetic field of a star is still much greater, that the outer pressure. In this case, the flow crosses the critical surfaces being still unaffected by the outer media. After that the flow is collimated somehow in a one-dimensional jet. We seek its internal structure in two cases: for a cold flow, and for flow with a finite temperature.

We regard the problem of the jet structure in a far region of the outflow, where the jet is already collimated by the finite pressure of external media. Thus, we use the approach of a stationary non-relativistic one-dimensional MHD. This approach can be formalized as Grad-Shafranov equation (representing the force balance across the magnetic surfaces) on the unknown magnetic flux function $\Psi(r,z)$, and the Bernoulli equation representing the energy conservation. The latter supplies The Grad-Shafranov equation with the matter density, or, equally, the Alfvénic Mach number — the quotient of the poloidal velocity to the Alfvénic velocity. These equations can be written as a set of ordinary differential equations for one-dimensional flow:

$$\frac{dM^2}{dr} = F(E, L, \Omega, \eta, s, M^2, \Psi, \text{and derivatives}), \qquad (2)$$

$$\left(\frac{d\Psi}{dr}\right)^2 = G(E, L, \Omega, \eta, s, M^2). \qquad (3)$$

Here $E(\Psi), L(\Psi), \Omega(\Psi), \eta(\Psi), s(\Psi)$ are the integrals conserved along the magnetic surfaces representing the conservation of energy, angular momentum, angular velocity, a quotient of a magnetic flux to a mass flux, and entropy respectively. F and G are known functions [6], and Ψ and M^2 are the unknown functions of r — the cylindrical radius — only. The integrals E, Ω, η, and s are to be found from the boundary conditions, and the integral L — from the regularity condition at the fast magnetosonic surface (FMS). The initial conditions for this set of equations is $\Psi(0) = 0$, $M^2(0) = M_0^2$, and the jet boundary is defined by $\Psi = \Psi_0$, where Ψ_0 is the full magnetic flux.

We assume that the outflow consists of two parts: the central part which is the outflow from a star, and the outer part — an outflow from a disk. For the central part we presume the outflow to be monopole-like. Thus, we use the integrals for a monopole flow: the constant Ω, η, s, and the linear functions E and L, which can be used for an inner part of a flow. We choose the integrals for the outer part of a jet so as to assure that Ω, B_ϕ, v_ϕ go to zero at the outer jet boundary. In this case there is a contact discontinuity at the radius where the jet is contacting with an outer media. We need to insure that there is a force balance at this boundary. This can be done by an appropriate choice of M_0^2.

Cold flow. Let us show that the cold model can not account for the observed jets. Indeed, the solution of equations (2) and (3) for a sub-Alfvénic flow gives us for the poloidal magnetic field in a jet $B_p = \text{const}$, and the value of this constant depends on $M_0^2 < 1$. There is a simple physical explanation why the homogeneous poloidal magnetic field is a solution of trans–field equation for a sub-sonic flow. The point is that for $M^2 < 1$ the energy density of the poloidal magnetic field $B_z^2/8\pi$ is much larger than both the energy density of the toroidal magnetic field $B_\varphi^2/8\pi$ and the energy density of particle $\rho v^2/2$. As a result, the trans–field equation can be rewritten as $d(B_z^2/8\pi)/d\varpi = 0$. Hence, for sub Alfvénic flows the homogeneous poloidal magnetic field is a solution of the trans–field equation for arbitrary invariants $E(\Psi)$ and $L(\Psi)$. On the other hand, one can find that for a maximal Mach number being equal to 1, the value of a minimal poloidal field $B \sim 10^{-1}$G. Hence, one can conclude that sub Alfvénic flow cannot be realized in the presence of small enough external magnetic field $B_{ext} \sim 10^{-3} - 10^{-6}$ G. Clearly, this result is in agreement with observational data – the jets we observe are supersonic.

It is known for a super-Alfvénic flow [10], that a poloidal magnetic field $B_p \propto r^{-2}$, which means that a magnetic flux function $\Psi \propto \ln r$. This, in turn, means that even the inner jet boundary is located exponentially far from the axis. But the magnetic field there is exponentially small, which contradicts to the finite outer media pressure.

Our numerical calculations of a trans-Alfvénic flow has showed that such a flow exists only for $\Psi(0) > 0$, which implies the delta-like magnetic field at the axis. Since we use the physically reasonable condition $\Psi(0) = 0$, we conclude that the trans-Alfvénic flow can not be a solution of our problem for a cold flow.

Thermal flow — an oblique shock model. We have found that there is no solution of our problem for reasonable physical parameters in an approach of a cold non-relativistic magneto-hydrodynamics. We suggest that the temperature plays a very important role in such a problem. Indeed, the flow crosses all the critical surfaces while the poloidal magnetic field is much larger than the outer magnetic field, and we can neglect the latter. As the super-fast sonic wind expands, the poloidal field decreases until it becomes comparable with the outer field. This situation is alike the pure hydrodynamic super-sonic flow meeting the wall. Unless the wall has a specially shaped form, the oblique shock stands. The flow heats additionally at the shock. We suggest that the same takes place for our model of a wind expanding in an outer space with a finite pressure. The hydrodynamic analogy is all the more reasonable as it is known that the flow is already weakly magnetized at the fast critical surface: $W_{part}/W_{part+em} = 1/3$. The effects of a shock are important and could not be included in a cold wind model. So, let us regard the problem with a finite temperature.

In order to do this we must find the entropy jump at the shock. All the rest integrals of motion are unchanged there. The problem of finding the oblique shock shape in the full MHD model is very complicated, so we will estimate the entropy jump using the following simplifications: a monopole hydrodynamic super-sonic outflow with a zero angular momentum meets the cylindrical wall (which models external media). For this model we seek the shock position so as to turn the monopole flow into cylindrical flow. This can be done up to the some maximal spherical angle θ_{max}, which depends on the sonic Mach number before a shock. For the greater spherical angles we use the shock inclination to a flow the same as at the θ_{max}, and the flow has still a radial velocity component there. The flow behind a shock remains super-sonic close to the axis, and becomes sub-sonic for a greater spherical angles. We assume that the sub-sonic part of a flow will again be accelerated to a super-sonic velocity as it still widens, and the final turn into cylinder will occur at the sonic surface. We use a hydro-dynamic approach because the flow is already weakly magnetized at the FMS, so we expect that the magnetic effects will not change the shock properties crucially. We neglect the angular momentum since only a normal to a shock velocity component defines the properties of a shock, as a shock normal has only poloidal components for the symmetry reason. Modelling the oblique shock position as explained above, we get the only unknown integral for a thermal flow — the entropy of a flow. Of course, this estimate is very preliminary, although it still allows us to construct a one-dimensional jet with a properties consistent with the observations. We hope to get the correct shock position for the full magneto-hydrodynamic 2D numerical simulations performed by T.Yelenina.

Results. We solve the equations (2) and (3) numerically, using the following parameters of our model: the magnetic field at the star surface $B_0 = 10^3$G, the initial ejection velocity of a matter at the star surface $v_{in} = 10$ km/s, a temperature at the star surface $T_0 = 3 \cdot 10^6$K, the politropic index $\gamma = 1.5$, angular velocity of a star $\Omega = 10^{-5}$ s^{-1}, radius of a star $R_{in} = 10^{11}$cm, an external magnetic field $B_{ext} = 10^{-3}$G, $\dot{M} = 10^{-8}$ M$_\odot$/yr, and $M_0^2 = 2$. Such model parameters give us the following properties of a jet itself in a far region: the jet boundary $R_{jet} = 10^{15}$cm, for a central part of a flow $v_p = 100 - 600$km/s, $v_\phi = 10 - 60$ km/s, and the temperature of a central part of a flow $T = 1000 - 5000$K, while the outer part has a temperature $T = 10 - 100$K. All this parameters are in good agreement with the observations.

We have constructed the internal structure of a non-relativistic jet observed in YSOs. We have found that even the one-dimensional model of the already collimated flow puts some restrictions on the inner outflow: we need the oblique shock to construct a solution to a one-dimensional problem. Even the preliminary model of a shock provides us with the jet properties which are consistent with the observations.

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