A 2D Model of Non-Stationary Accretion onto a Magnetized Neutron Star

V.V. Grigoryev[1], A.M. Krassilchtchikov[2]

E-mail: *vitaliygrigoryev@yandex.ru, kra@astro.ioffe.ru*

A 2D non-stationary model of column accretion over the surface of a magnetized neutron star is presented. It is found that collisionless shocks appear and evolve in the column on the time scales of about 10^{-7} s, and their surface is not flat. A significant non-uniformity of flow parameters across the column is observed. In general, the modeling results agree with those of the previously developed 1D model.

1 Introduction

Accretion onto compact stellar objects was recognized as an efficient source of hard X-ray emission already 50 years ago [1, 2]. Ya.B. Zeldovich [3, 4] showed that the spectrum emitted from the vicinity of a neutron star surface critically depends on the accretion regime, namely, on whether the infalling matter comes as separate particles (free-fall) or as a hydrodynamic flow.

The accretion models developed in 1970–80 postulated the existence of a collisionless shock in the column, and its height over the surface of the star was a model parameter. However, for the substantially super-Eddington case J. Arons and R. Klein [5] and their collaborators [6] showed that non-stationary radiation-dominated shocks appear and evolve in the accretion column.

Apart from gas dynamics in an accretion column, some studies were devoted to the problem of radiation transfer in the column. Thus, R. Araya, A. Harding considered the influence of Compton processes on the transfer of cyclotron line emission and computed line profiles for a set of column parameters [7].

In 2004 A.M. Bykov and A.M. Krassilchtchikov [8] developed a 1D model of non-stationary accretion in a column of a magnetized neutron star. They did not postulate the existence of a shock in the column, rather, such a shock appeared as a natural result of evolution of an accreting flow. In this model a collisionless shock formed on the scales of 10^{-5} s. Thus, the aim of the present work was to extend the model of [8] to the 2D case and compare the resulting flow profiles.

[1] St. Petersburg State University, Russia
[2] Ioffe Institute, St. Petersburg, Russia

V. Grinin et al. (eds) Radiation mechanisms of astrophysical objects. Yerevan: Edit Print, 2017, pp. 305–310.

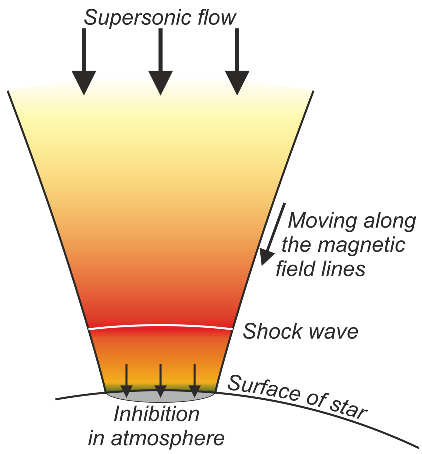

Figure 1: A sketch of the modeled accretion column.

2 The accretion column model

We consider a numerical model of sub-Eddington non-stationary accretion in a 2D column over a magnetic pole of a neutron star. We do not postulate the existence of a shock in the column as an initial condition. The model takes into account various interactions of two sorts of particles (electrons and ions) within the infalling hydrodynamical flow, as well as interaction of the plasma and radiation field. We consistently describe the dynamics of the plasma flow in the strong magnetic field of the star which is considered stationary. A sketch of the modeled system is presented in Fig. 1.

One of the main features of the presented model is a Godunov-type hydrodynamical approach which allowed us to treat discontinuous flows and describe shocks dynamics. Another feature of the model is the use of 2D dipole geometry, which is a natural choice to describe the flow of gas along the force lines of the dipole magnetic field.

The main global parameters of the employed model are as follows: the accretion rate $\dot{M}$ (typically $\dot{M} \sim 10^{15}$ g/s), the induction of the dipole magnetic field of a neutron star B ($\sim 10^{12}$ G), the radius of the star ($\sim$10 km), the mass of the star ($\sim$1.4 Solar mass), the area of the accretion spot on the star surface (~ 1 km^2).

3 Input physics and the numerical approach

The accreting plasma flow is treated in the 1-flow hydrodynamical approximation, due to the very short time scale of 2-flow instabilities. Hence, we model a flow of two fluids (electrons and ions) moving at the same velocity, but having different temperatures. The magnetic field of the neutron star is kept constant on the considered times scales.

The flow evolution is described by the following set of equations:

$$\begin{cases} \frac{\partial \rho}{\partial t} + \mathrm{div}(\rho \vec{u}) = 0, \\ \frac{\partial (\rho \vec{u})}{\partial t} + \nabla P + \nabla \cdot (\vec{u} \oplus (\rho \vec{u})) = \vec{\mathcal{F}}, \\ \frac{\partial}{\partial t}\left[\rho_s\left(E_s + \frac{u^2}{2}\right)\right] + \mathrm{div}\left[\rho_s \vec{u}\left(E_s + \frac{u^2}{2}\right) + p_s \vec{u}\right] = \mathcal{Q}_s, \end{cases} \tag{1}$$

where $\rho = \rho_e + \rho_i$, $p = p_e + p_i$, $\mathcal{F}$ and $\mathcal{Q}_s$ denote the sources of momentum and energy, respectively, and s is the sort of particles (i for ions, and e for electrons).

The set has to be completed with equations of state for each sort of particles. The ideal gas approximation $E_s(\gamma_s - 1) = p_s/\rho_s$ is valid for the considered ranges of temperatures and densities, but to account for the mild relativism achieved at the highest temperatures of the flow, we treat the adiabatic indexes as temperature-dependent values.

For mildly relativistic particles ($k_B T_s \ll m_s c^2$) the adiabatic index can be approximated as $\gamma_s \approx \gamma_{0s}\big(1 - \frac{k_B T_i}{m_i c^2}\big)$ [9], where $\gamma_{0i} = 5/3$ is the usual non-relativistic value for particle distributions with 3 degrees of freedom, and $\gamma_{0e} = 3$ as the electrons appear quasi-one-dimensional in the considered strong magnetic fields.

As we consider both the (resonant) cyclotron line emission, which provides substantial radiative pressure on the flow, and the (non-resonant) continuum emission, the transfer equation is solved by numerical iterations via a custom 2-step procedure with different emission and absorption coefficients at each step.

The force term $\vec{\mathcal{F}}$ is the sum of several forces: the gravitational force, the non-resonant and resonant radiative forces, and the viscous resistive force in the atmosphere of the neutron star (which is, in fact, an extended boundary condition at the bottom of the correction column). The force of resonant radiation acting on the electrons accounts for the scattering phase function (according to [10]), while the non-resonant force is due to Thomson scattering.

The ions change their energy due to the following processes: small-angle scattering with the electrons, collisional excitation of electrons to Landau levels, collisional relaxation in the atmosphere, and the work of the effective ambipolar force.

The electrons change their energy due to the following processes: small-angle scattering with the ions, Bremsstrahlung cooling in collisions with electrons and ions, excitation to Landau levels in collisions with electrons and ions, Compton processes, and the work of the effective ambipolar force.

The complete set of equations is rewritten in dipole geometry and numerically integrated. As the multi-component accreting flow may contain discontinuities, in particular, shocks, a modified Godunov-type approach [11, 12] has been employed. The radiation transfer equation is integrated within a first order finite-difference scheme.

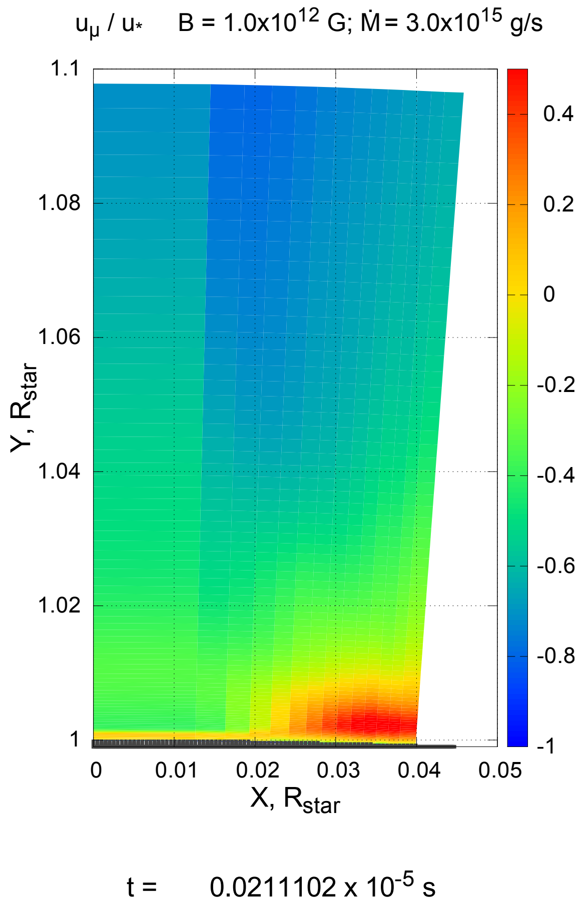

Figure 2: Distribution of velocity projection along the field lines (color) in the cross section of the accretion column.

4 Results

The performed modeling showed collisionless shocks to appear and evolve on the time scales of about 10^{-7} s. The 2D modeling also allows to see that the surface of the evolving shock is not flat, but rather resembles an "upside down hat": at the borders of the column the shock position is higher than over the pole.

A cross section of a modeled column (projection of 2D velocity onto the field lines) is shown in Figs. 2 and 3 to illustrate the form of the shock.

The 2D model allowed us to account for the flow motion and radiation transfer across the force lines. We also implemented an improved approach to the treatment of radiation transfer accounting for the scattering phase function both for non-resonant and resonant emission.

The presented results of 2D modeling are consistent with those of the 1D model [8]. Namely, the column profiles of accreting plasma parameters of the 2D model near the pole force line are in a qualitative agreement with the profiles

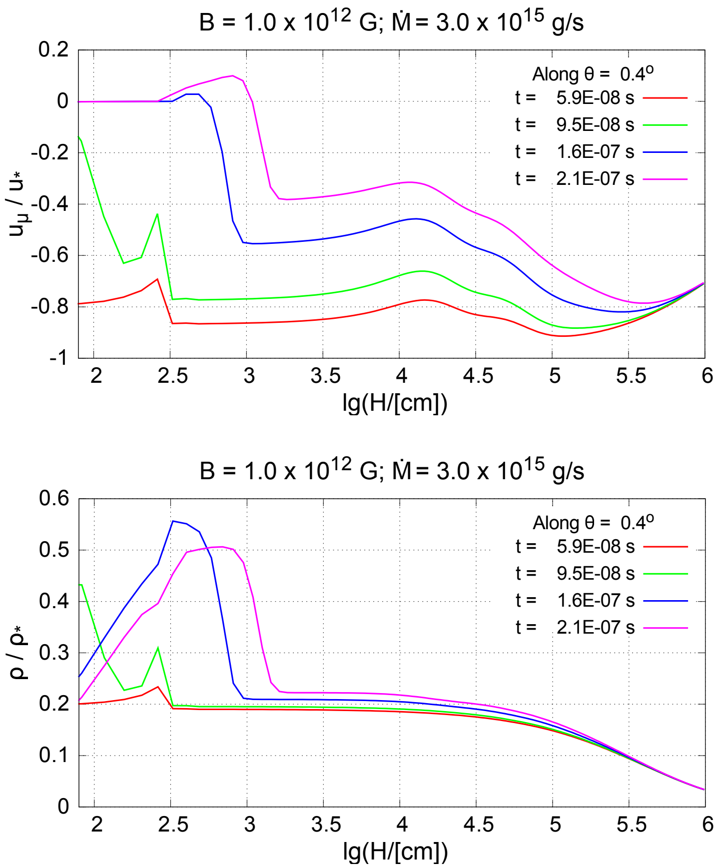

Figure 3: Velocity projection (up) and density (down) along the force line started at the magnetic pole, normalized by $u_* = 1.9 \times 10^{10}$ cm/s and $\rho_* = 10^{20}$ g/cm^3, respectively.

obtained with the 1D model. However, with the new model we also obtain a new effect which could not have been studied before – the inhomogeneity of the flow across the field lines.

References

1. *Ya.B. Zel'dovich*, Dokl. Acad. Nauk SSSR, **155**, 67, 1964.
2. *E.E. Salpeter*, Astrophys. J., **140**, 796, 1964.
3. *Ya.B. Zel'dovich*, Trans. XIII IAU Meet., Prague, 1967.
4. *Ya.B. Zel'dovich, N.I. Shakura*, Astron. Zh., **46**, 255, 1969.
5. *R.I. Klein, J. Arons*, Proc. 23rd ESLAB Symp. on Two-Topics in X-Rays Astronomy. Noordwijk, 1989, p. 89.
6. *R.I. Klein, J. Arons, G. Jernigan, J.J.-L. Hsu*, Astrophys. J. Lett., **457**, L85, 1996.
7. *R.A. Araya, A.K. Harding*, Astrophys. J., **517**, 334, 1999.

8. *A.M. Bykov, A.M. Krasil'shchikov*, Astron. Lett., **30**, 351, 2004.
9. *S. De Groot, W. van Leeuwen, Ch. van Weert*, Relativistic Kinetic Theory. Amsterdam: North-Holland, 1980.
10. *A.K. Harding, D. Lai*, Rep. Prog. Phys., **69**, 2631, 2006.
11. *S.K. Godunov, A.V. Zabrodin, M.Ya. Ivanov et al.*, Numerical Integration of Multidimensional Gas-Dynamic Problems. Moscow: Nauka, 1976 (in Russian).
12. *R.J. LeVeque*, J. Comput. Phys., **131**, 327, 1997.

* The color figures are available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.