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Exoplanetary magnetodisc in a context of other types of astrophysical discs

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Abstract

The accreting ionized gas surrounding a neutron star or a white dwarf creates an accretion disc. For definite parameters of the system, radius R_A (the Alfven radius), where the magnetic energy density is equal to the kinetic energy density, is close to the inner boundary of disc, there plasma leaves the accretion disc and flows to the central object. Accretion disc in a binary system will be disrupted at a radius R_A. The heliospheric current sheet's inner edge is also located at the Alfven radius. The same is true for discs in the magnetospheres of giant planets of the solar system - Jupiter and Saturn: their inner edges are located at the Alfven radii. Due to the star-exoplanet interaction, a magnetosphere arises around a magnetized planet placed in close orbit about the host star ("Hot Jupiter"). In the equatorial plane of exoplanet's magnetosphere a magnetodisc could be formed by thermal expansion and mass loss of the planetary atmosphere heated by stellar XUV with the consequent ionization of the expanded gas. The distance to disc's inner edge determines the disc's magnetic moment, the total magnetospheric magnetic field, and the size of magnetosphere. Here we pay attention to the fact that the Hot Jupiter's disc inner edge location at R_A [3] coincides with locations of the inner edges (roughly at the Alfven radii) of some other astrophysical discs (for definite parameters of the system included them) independent of a nature of their origin and of the direction of motion in the discs, which means that in such discs the kinetic energy density exceeds the magnetic field energy density.

1. Introduction

A paraboloid model of the Hot Jupiter's magnetosphere including a magnetodisc is constructed in [3]. During the thermal outflow of atmosphere of close-in Hot Jupiter, the upper layers of the expanding planetary atmosphere, ionized by stellar radiation, contribute to the formation of extended current-carrying plasma disc around the planet. The magnetodisc-dominated magnetospheres could be large enough to protect exoplanets against the destructive action of the stellar wind plasma flows. The main magnetospheric magnetic field sources in the paraboloid model of an exoplanet are: the intrinsic planetary magnetic field, magnetodisc, the tail current system, and the magnetopause shielding currents [3]. Location of the inner edge of magnetodisc is proposed to be at Alfven radius, while its outer edge is close to the magnetopause substellar distance.

We consider several kinds of discs surrounding different rotating magnetized celestial bodies and note that many of them for the definite parameters have the inner edges connected with the Alfven radii. Of course, the other types of discs also exist, for which the inner edges do not coincide with the Alfven radii (the galaxy discs, the discs around supermassive black holes/quasars, the accretion discs around stars with weak magnetic fields, etc.), but here shortly discussing some of the astrophysical discs, we pay the main attention to the first group of them. Real discs are more complicated and strongly stratified than those presented in the simulations and theories, however, we would like to emphasize that the described effect (location of the inner disc's boundary close to the Alfven radius) exists in numerous forms in the universe.

2. Discs around stars and planets

In models for disc accretion onto magnetized objects, the inner radius R_0 of the Keplerian disc is conventionally expressed in the form $R_0 = \xi R_A$, where R_A is the Alfven radius for spherical accretion and the parameter ξ is usually taken to be 0.5 [2]. In disc-fed X-ray pulsars, the inner radius R_0 of the accretion disc is also expressed in terms of the Alfven radius R_A for spherical accretion, $R_0 = \xi R_A$ [4]. Application of the beat frequency model to binary X-ray pulsars with quasi-periodic oscillations suggests that for these objects the stellar dipole field essentially fully threads the disk and $\xi \cong 1$. Strong magnetic accretors are the accreting neutron stars. Some of them possess accretion discs, while the others are accreting directly from the surroundings. Following a supernova explosion, some part of the ejected matter may remain bound to the remnant and fall back. A disc may be formed of this material if its specific angular momentum l exceeds the Keplerian value at the surface of a newly formed neutron star, $l_K = (GM_*R_*)^{1/2}$, where M_* is the mass of the star and R_* is its radius. The behavior at the inner edge of this accretion disc depends on the neutron star's magnetic field. There is a class of neutron stars for which the inner edge of the disc is located where the integrated magnetic stress acting on the disc becomes comparable to the integrated material stress associated with plasma inward radial drift and orbital motion (at Alfven radius). A neutron star can interact with a surrounding disc in a variety of modes (accretor, propeller, and ejector) determined by the location of the inner radius of the disc with respect to the corotation radius and the light cylinder radius. In a binary system with accretion disc, this disc is disrupted in a region where magnetic and matter stresses are comparable, and the inner radius of the disc, R_0, is estimated by balancing the kinetic energy density of the disc with the electromagnetic energy density of the radiation generated by the neutron star.

In model used in [1], in a compact binary system with magnetar and a massive companion star of the O, B type, the inner boundary of disc was located at the Alfven radius. The mass from the stellar wind was captured by the strong gravitational potential of the magnetar in the propeller phase. At the inner disc's edge electrons are accelerated up to TeV energies. These electrons produce gamma-ray emission.

For typical models of the magnetized solar wind, the Alfven radius is 0.11 AU. It is generally assumed that the heliospheric current sheet's inner edge is located at the heliocentric distance where the solar wind velocity equals to the Alfven one (at R_A). In the solar system the jovian magnetodisc starts from ~18 R_J, while Alfven velocity equals to the corotation velocity at 18 – 20 R_J (R_J is the jovian radius). At Saturn for the Pioneer 11 epoch the inner radius of the kronian magnetodisc/ring current was 6.5 R_S, and R_A was 6-8 R_S (R_S is the kronian radius).

In the model of the Hot Jupiter magnetosphere presented in [3] it is suggested that as the gas/plasma surrounding the rotating magnetized star moves outwards along the magnetic field lines, its angular velocity is approximately constant until speed V_φ reaches a value of Alfven speed V_A, when magnetic tension balances the centrifugal force per unit mass. There, at Alfven radius the field lines are distorted by the inertia of the gas. At the Alfven radius due to the azimuthal velocity shift the field-aligned currents may be generated. Finally the disc is formed with the inner edge near the Alfven radius.

3. Conclusions

Here we emphasize that for definite parameters an expanded range of astrophysical discs exists whose inner edges are expressed in terms of Alfven radii independent of the nature of discs origin, of the motion direction inside the disc (towards the central body or out of it), of the sort of gas/plasma in the disc, and of matter behavior outside the disc, because the kinetic energy density in disc exceeds the magnetic energy density. At the inner edge of these discs due to change of magnetic field lines form, the azimuthal velocity shift arises and accelerated particle flows and field-aligned currents could be generated.

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