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On the Solar Wind Origin Problem and its History

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Abstract. The history of ideas about the solar wind origin contains interesting paradoxes and unsolved issues. The classical Bondi model (1952) demonstrates that solar type stars can exist without wind or even in the states of accretion. They can be searched in EUV Doppler shift measurements. The solar wind origin problem has only one evolutionary solution. At the present time, the fastest solar wind streams are driven by preponderant expelling electromagnetic forces in the corona and not by thermal pressure gradients here.

Keywords: solar wind origin, interstellar medium, models.

1 Introduction

The spherically symmetric model of the quasi-steady polytropic flow in the stellar atmospheres placed in the gravity field of a central body was first considered in detail by H. Bondi [1]. The model is fundamental, very simple and physically tractable for analytical considerations. It takes into account in some approximate way the conservation of mass, momentum and energy. The angular momentum is assumed to be zero in this model. Three admissible types of solutions of the governing Bernoulli equation are available in this model: 1) static $v=0$, 2) expanding wind type flow $v>0$, 3) contracting accretion type flow $v<0$, where v is the radial velocity. The selection between those bifurcated non-zero types depends on the imposed internal and external boundary conditions. This means that the solar wind origin problem can be not properly addressed nor completely explained in the framework of this steady state model alone without additional assumptions.

Paradoxically enough, this model was initially developed in attempts to explain the existence of the hot solar corona by the accretion. According to those early ideas, which are physically sound, but not appropriate for the contemporary Sun, the potential energy of the external gas in the gravity field could be transferred to the energy of the falling material and finally after deceleration near the Sun to the heat in the corona. We understand now that it is generally not the case for the contemporary Sun.

Contrary to this, looking at the same theoretical model equations, it was assumed that the outflow of gas “to be the secondary effect” based on the ideas that “we do not know of any mechanism which might result in gas leaving the sun at 1000 km/s and which do not originate as a consequence of a high coronal temperatures" [2]. This stand point is logically not quite satisfactory: "we do not know" does not mean "does not exist…". For example, Ampere forces acting across electric currents and magnetic fields can be (and appear indeed) the drivers of big and small eruptions on the Sun in many instances. More appropriate and complicated non-steady state and inhomogeneous models are still not well developed.

Nevertheless, the Bondi model showing a bifurcation is useful for the demonstration of the necessity of the time dependent approach and for obtaining a physically correct answer to the long standing question: why the solar wind blows? The tentative answer arises: it is not only because of the instantaneous hot corona and rarefied interstellar medium around the Sun, as was assumed [2], but also because of the evolutionary state of the given star. Solar-like stars of the same type as our Sun can exist with hot corona and situated in a rarefied interstellar medium, but without any wind or even in the accretion state [3].

The existence of such stars (acceptors) is not prohibited by any physical laws and could be searched in EUV line Doppler measurements as well as other solar-type stars similar to the Sun in this respect (donors). Donors and acceptors can be isolated or grouped in binary or more complicated associations of stars. We consider in this paper several aspects of the problem and discuss its history.

2 Three Aspects of the Solar Wind Origin Problem

Astrophysical aspect. It assumes the global approach and evolutionary considerations at largest time scales. Easy solutions were suggested in frameworks of ad hoc naïve models and conceptual scenario. Not uniqueness is obvious.

Evolution and prehistory of the star is important for the correct problem statement with unique solution. In this sense, the solar wind origin problem is not well determined because of scarce input information. We can not definitely indicate when and how the solar wind started to blow.

When the accretion on the Sun was ended? It is also an ill posed question. The accretion is still going, but it is not a dominant process in the balance of the mass. The rest mass of the contemporary Sun is gradually diminishing mainly via photon and neutrino emissions according to standard models and available observations. Solar wind and interstellar material accretion on the Sun play a secondary role in the energy and momentum budgets of the Sun at present time.

The energy and mass needed for the solar wind losses are supplied from solar interiors by convection. The solar wind channel of the mass loss is small, but comparable with the main rest mass losses via white light and neutrino emissions of our Sun. This approximate balance can be an indication for future models of the plasma outflow and radiation transport from the Sun in the long term scale.

The momentum transported by the solar wind (its dynamical pressure density) is about three orders of magnitude below the pressure of the white light emitted by the Sun at a given distance in the outer corona and in the heliosphere. Corresponding energy flux densities differ by 5-6 orders of magnitude. Hence, a tiny portion of the available free electromagnetic energy flux is sufficient to feed the solar wind energy losses. Those fluxes are decoupled in the transparent solar atmosphere, but not in the opaque interiors. We still do not have a satisfactory theory of the energy transports from the convection to the radiation immediately in the semitransparent zone beneath the photosphere.

The material of the corona is refreshing each couple of weeks or so depending on the level in the atmosphere, when the chromosphere and photosphere permanently survive for many years against the bulk outflow. They represent upper parts of the turbosphere around the Sun. Let us remind that the turbosphere encompasses the shells around the Sun and inside the Sun where turbulent velocities of up- and down-flows as well as lateral motions are bigger than the regular radial outflow.

Plasma physical aspect. Local approaches are more elaborated. What are operating ‘mechanisms’ of the solar wind formation? Simple and complicated answers are available, but they are not always convincing and final in the current literature.

The solar wind is supersonic only regarding the sound speed of the ion (proton) gas components. The solar wind is essentially subsonic regarding the electron gas component. The resulting radial expansion velocity of the solar wind is intermediate between ion thermal and electron thermal speeds. The expansion process resembles the ambipolar diffusion with the velocity close to the geometric mean of those two speeds mediated by the electric fields and the square root of ion to electron mass ratios. The semi kinetic three fluid model presents a flexible description of those regimes taking into account the quasi neutrality especially in the non-steady state situations [4].

Coupled astrophysical and plasma physical aspect.

Intermediate space-time scales are involved. Non-local and non-linear problems should be considered. Solutions are not easy and complicated. Measurements and theory show that turbulence and radiation transports are also involved without any doubts in the energy and mass transports leading to the mass loss of the Sun ultimately observed as the super-magneto-sonic wind outflow. Is it a simple and tractable problem?

3 Stars-Donors and Stars-Acceptors of Interstellar Matter

Stellar objects of the solar type can probably exist in the state of accretion (acceptors). This can be checked when EUV line spectra and Doppler shifts carefully observed of T-Tauri and other stars. Hydrogen-like ions are especially suitable for this purpose because of simpler spectroscopy of lines needed for the interpretation of observations of red- and blue-shifted wings. Geometry constraints are difficult and need some a priori assumptions about the models which can be checked only step by step. The solution of inverse problem is not easy task.

Inflows and outflows can be not excluded to exist simultaneously or intermittent in space and time for parts of the surface of the same stellar object. They can be overlapped on the line of sight. They can be also non steady state switched in and off depending on the transient boundary conditions on the star and its local stellar and interstellar surroundings. Analytical and numerical considerations of this kind can be found in the literature [7-9], indicating that the solar wind origin problem can be not solved properly if the prehistory is not considered. At the moment, the convincing solution of this problem is lacking. The problem urges non steady state and evolutionary models, which are difficult and not well developed as yet.

More important is that the admissible physical solutions are not unique in the framework of available models because of nonlinearity. Only additional observational constraints can resolve this remaining ambiguity and select the adequate mathematical solution. Any physical or mathematical theory per se is not enough for this purpose. The solar wind origin model is a typical incorrect mathematical problem in this sense and needs a regularization procedure for obtaining the uniquely determined solution.

When and how the transition occurred from the acceptor to the donor state in the case of the Sun? The answer is not clear. Existing theoretical arguments based on the instability considerations (see e.g. [7-12]) are not sufficient to answer this fundamental question without further observational input information. Available observations relate to early T-Tauri type stars (see e.g. [13]).

Two hypotheses are conceivable about this transition: 1) simultaneously with the transition from laminar to the turbulent convection state (Hayashi phase transition), 2) simultaneously with the start of the thermonuclear burning in the core (Bethe cycles). Other options not excluded. More studies are needed.

4 Discussion

The beautiful term ‘solar wind’ was probably coined in a brief scientific note in 1919 [14] and forgotten for a long time. The bulk properties of the permanent and transient corpuscular streams from the Sun were not known in a sufficient quantitative measure and only started to be guessed at that time. K. Birkeland even earlier supposed those corpuscular streams consisting of positive ions and negative electrons. The quasi neutral plasma concept aroused in 1920-th.

The solar wind blows not only because of the hot corona or because of the thermal escape of hottest parts which are heated by some mechanisms and expelled by thermal stresses from the gravity field of the star through the ‘Laval nozzles’. Those ‘thermal’ mechanisms on the Sun contribute, of course, in many instances. Additional acceleration in kinetic regimes plays the role without any doubts in the outer corona where collisions are rare and the turbulence is developed. Solar wind origins are essentially turbulent [15].

Magnetic ‘pumps” also working on the Sun not less efficiently. Magnetic stresses are locally playing an important role for expulsion of plasma from the gravity field of the Sun. “Ulysses” mission convincingly demonstrated that magnetic drivers of the solar wind dominate over thermal gas pressure ‘machines’ in big circumpolar coronal holes where the magnetic pressure is larger than the thermal one (low beta regimes). There is no doubt that electric drifts, Ampère forces and numerous plasma waves propagating outwards entrain the coronal material away from the Sun and produce the wind in combined action of those and other drivers.

Thermal drivers of the motions are more important in the lower parts of the solar atmosphere. Magnetic forces dominate at larger distances. The ratio of magnetic versus thermal drivers of the motions in the solar corona seems to be dependent on the situation, the altitude (increasing with the height in the atmosphere of the Sun), positions on the Sun, and on the solar cycle (being higher in the minimum and lower in the maximum of activity). In this sense, the longstanding solar wind origin problem has multiple solutions. There are many sources and many physically different mechanisms operating on the Sun and leading to the hot corona and the solar wind outflow.

The fastest transient solar wind flows have velocities up to 1-2 Mm/s and even more after strongest solar eruptions. Telescopic observations and multipoint in situ measurements in the heliosphere demonstrate that those flows often have loop-like shape and directed across the magnetic field with strong shocks. This is indicative of the Ampere force and the electric drift dominance as driving mechanisms. We will not go in complicated details of the fastest solar wind formation regions, but mark only that more developed theoretical models (see e.g. [16]) consider the field aligned flows in open magnetic configurations (coronal holes, funnels). Wave and turbulence dissipation are viable mechanisms of the momentum and energy transports.

The lowest velocities in the solar wind can be even submagnetosonic, but those situations are rare and also transient. They appear sometimes in the trailing edges. The orientation of the magnetic field tends to follow Archimedian spirals because of the solar rotation, but with big deviations up to purely radial directions. Thermal pressure gradients play the role, of cause. Intermediate velocity wind is driven by the combination of magnetic and thermal stresses in the solar atmosphere.

One can see that assertions in literature during past 50 years that the solar wind is driven by the thermal pressure are not quite correct and need essential revision (see also the papers presented by S. Owocki [5] and A. Roberts [6] at the Solar Wind 12 conference for more details, further references and discussions of the situation).

The same can be said about distorted historical perceptions expressed in some publications that the existence of the solar wind was ‘predicted’ in 1958-1963. At that time and even much earlier, its permanent existence and correct orders of magnitude for density, velocity and temperature were known for a number of German scientists (see e.g. [17] and references there). This knowledge was not generally accepted. It was confirmed, refined and finally accepted by majority of specialists and broader community in the international scientific establishment after a long history of studies, which is still continuing.

Finally, we should not forget about the important role of rotation of the star and the matter around it. Angular momentum conservation law brings more diversity which is not well investigated as yet and difficult to evaluate a priori for the Sun. From one side, rotation can facilitate the escape of matter due to centrifugal catapult effect. From the other side, the opposite tendency can be caused by the suck of the vortex depletion region. The investigation of stability of those complicated regimes and time dependent theoretical models are beyond our scope here.

5 Conclusion

All in all, we may conclude that solar type stars probably could exist with hot corona, but without the wind or even with the accretion dominance. The wind driving mechanisms are diverse and numerous in the case of the Sun and other stars.

The question about the main driving mechanisms of the wind from the Sun as a whole star is still open. It was not solved as yet and can be not solved correctly and in a sufficient depth by existing theories in unique way without additional evolutionary information and observations. The history of the solar wind origin problem is not finished and needs further efforts.

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