Solar wind origin problem in two aspects: astrophysics and plasma physics

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Motivation

- **It is not known** when and how the solar wind started to blow. There are evidences that it existed on the geological time scale and will continue to exist even during crossing of dense galactic arms by the Sun in future.
- The Hayashi phase (beginning of convection) or the ignition of the thermonuclear burning could be an evolutionary benchmark in this respect, but details are not elaborated.
- It is often **assumed** as plausible (but not proven) in available macroscopic and kinetic plasma theories that the solar wind exists because of the hot and dense corona with high pressure of gas and magnetic fields from one side near the Sun and rarefied low density, low temperature and low magnetic fields in the interstellar medium surrounding the Sun from the other side.
- Nevertheless, all these conditions are compatible both with inflow (accretion) and outflow (breeze and wind) branches of the same quasi steady politropic model solution of the Bernoulli equation without jumps as considered by Bondi (1952) and Parker (1957). **Twice eroded problem.**

Governing MHD equations with dissipation and radiation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0, \qquad (1)$$

$$\rho\left\{\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}\right\} + \vec{\nabla} p - \frac{1}{4\pi}[[\vec{\nabla} \times \vec{B}] \times \vec{B}] + \qquad (2)$$

$$+ \vec{F}_{viscous} + \vec{F}_{gravity} = 0$$

$$\frac{\partial}{\partial t}\left(\rho u + \frac{1}{2}\rho v^2\right) + \frac{\partial}{\partial x_i}\left(\rho v_i w + \rho v_i \frac{v^2}{2} + \rho v_k \sigma'_{ik} - \kappa \frac{\partial T}{\partial x_i} + \right.$$

$$\left. + \frac{1}{4\pi} e_{ikl} e_{lmn} v_m B_k B_n + \frac{c}{4\pi\sigma} e_{ikl} j_k B_l\right) = -L + A$$

Eroded problem

- The solution of the quadratic equation is twice eroded and can only depict, but not predict the situation, which is totally prescribed by **initial and boundary conditions** at the star and in the interstellar medium around it.
- The definitive answers to the posed questions can be found only based on **time dependent theories** and observations. The magnetic, thermal and gravitational pumping of the material in the atmosphere of the star can proceed (and observed indeed) in both directions – away from the star and towards the star along finite (convective) or infinite (outflow/inflow) trajectories in kinetic or fluid approximations. Microphysical, macro-physical and global processes on the Sun and sun-like stars are non-locally and non-linearly coupled in a complicated way described by dimensionless scaling based on dissipative MHD and plasma kinetic equations with radiation.

Solar type stars without solar wind?

- The question about possible existence of solar-like stars with accretion of the plasma will be addressed. This possibility does not contradict any physical laws. Such objects should be searched on the sky with Doppler EUV measurements.

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Our suggestion

- Observe solar type stars
- Measure EUV spectral line profiles of Hydrogen like ions
- Doppler shifts (red and blue)
- Velocities of plasma motions?

First *in situ* measurements of the solar wind flux. Seminal works by K.I Gringauz and his coworkers. 1959

- Gringauz, K. I.; Kurt, V. G.; Moroz, V. I.; Shklovskii, I. S. Results of Observations of Charged Particles Observed Out to R = 100, 000 km, with the Aid of Charged-Particle Traps on Soviet Space Rockets, Astronomicheskii Zhurnal, Vol. 37, p.716, 1960 (Translated in English: Soviet Astronomy, Vol. 4, p.680, 1961)
- Gringauz, K. I.; Kurt, V. G.; Moroz, V. I.; Shklovskii, I. S. Ionized gas and fast electrons in the vicinity of the Earth and in interplanetary space, Planetary and Space Science, Volume 9, Issue 1-2, p. 21-25, 1962.
- Gringauz, K. I.; Bezrukikh, V. V.; Ozerov, V. D.; Rybchinskii, R. E. The study of interplanetary ionized gas, high-energy electrons and corpuscular radiation of the Sun, employing three-electrode charged particle traps on the second Soviet space rocket Planetary and Space Science, Vol. 9, p.97, 1962.

- Interpretation of measurements done in 1959 with ion traps on lunar rockets: Third radiation belt? No! Corpuscular streams from the Sun. Confirmation of the permanent, but variable flux of the order of 10^8 cm $^{-2}$ s $^{-1}$ by Mariner 2 during two months in 1962 (M. Neugebauer and C.W. Snyder, 1962).
- Solar wind idea was accepted by majority only since that time (1962).

Comment on the history of science about the solar wind

- Correct orders of magnitude for density, velocity and temperature of the solar wind were know from observations long before the Space Era (see e.g. Kiepenheuer, 1953).
- The opposite statement by Parker (2007) that “none of pre-Space Age density estimates inferred from observations was correct” (pp.110-111 ibid) is in error.
- Correct estimates were not appreciated by ‘majority and authority’ in scientific establishment at that time, but it is another story, which has little common with real knowledge.
- The history continues…

- *Kiepenheuer K.O. (1953). Solar Activity, “The Sun” Edited by Gerard P. Kuiper. Chicago: The University of Chicago Press, 1953, p.322*
- *Parker E.N. (2007). Solar wind, in Y. Kamide and A. Chian (Eds.), “Handbook of the Solar-Terrestrial Environment”, Springer, Berlin, 2007.*

What was known about the solar wind before the works of K.I. Gringauz?

- Notions **‘Wind’, ‘Sonnenwind’** first appeared in the German literature and were used as synonyms to **Corpuscular Streams from the Sun**.
- Cometary tails clearly indicated: **Permanent, but variable** wind.

(L. Biermann, Zs. f. Ap. 1951, K.O. Kiepenheuer, 1953).

Prehistory

- Other indirect evidences: geomagnetic storms (S. Chapman and J. Bartels), cosmic ray modulation (Forbush effect), dynamic corona (‘Kiev school’), evaporation (S.B. Pikel’ner), different theories of coronal gas etc.
- Correct orders of magnitudes were known for a long time before the Space Era (K.O. Kiepenheuer, 1953) for the wind: $n \sim 1\text{-}10^3$ per cm^3 , $V \sim 300\text{-}600$ km/s, Mach number 2-3.5 (suprathermal expansion of corona!) but they were not accepted by ‘majority and authority’ including S. Chapman and many others, who argued against the permanent coronal expansion (without sufficient grounds…).

I.S. Shklovskii (1962) admitted existence of the interplanetary plasma in rest and not moving from the Sun in the interplanetary space even after joint works with K.I. Gringauz.

He did not accepted the theory of supersonic expansion given by E. Parker and wrote about incorrect selection of integration constants (“Physics of Solar Corona”,1962, see also the English translation of this book in 1965).

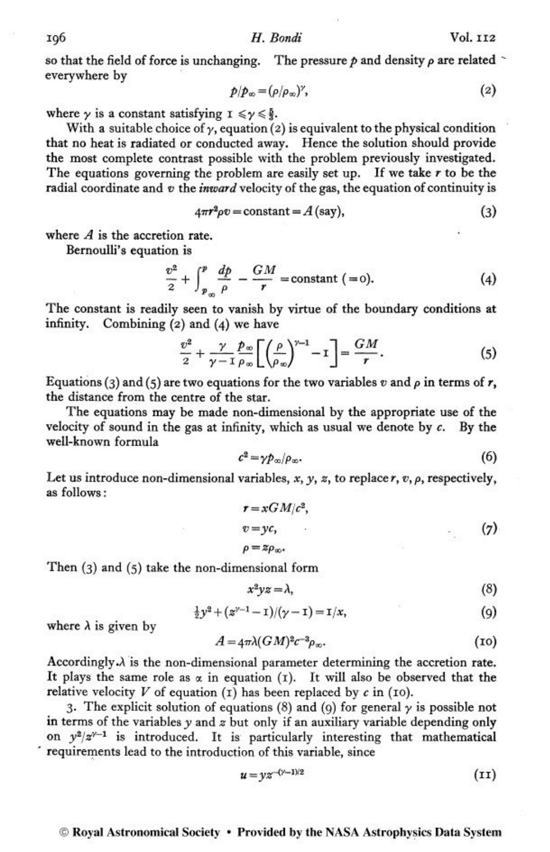
+V or –V

Breeze (wind) or accretion on the Sun?

- Both processes are taking place, but the wind dominates at the present stage of the evolution of the Sun and its neighborhoods (stars and interstellar medium).
- Proto-solar cloud was formed due to gravitation instability from the cool dust-gas cloud in the distant past.
- Open question: is it possible to find solar type stars without wind or with accretion of hot corona (Bondi)? Not excluded, probably **yes**.

Bondi, 1952

(Bondi, H., On spherically symmetrical accretion,
Monthly Notices of the Royal Astronomical Society, Vol. 112, №.2, p.195-204, 1952)



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so that the field of force is unchanging. The pressure p and density ρ are related everywhere by

$$p/p_\infty = (\rho/\rho_\infty)^\gamma, \tag{2}$$

where γ is a constant satisfying $1 \leqslant \gamma \leqslant \frac{5}{3}$.

With a suitable choice of γ, equation (2) is equivalent to the physical condition that no heat is radiated or conducted away. Hence the solution should provide the most complete contrast possible with the problem previously investigated. The equations governing the problem are easily set up. If we take r to be the radial coordinate and v the *inward* velocity of the gas, the equation of continuity is

$$4\pi r^2 \rho v = \text{constant} = A \text{ (say)}, \tag{3}$$

where A is the accretion rate.

Bernoulli's equation is

$$\frac{v^2}{2} + \int_{p_\infty}^{p} \frac{dp}{\rho} - \frac{GM}{r} = \text{constant } (=0). \tag{4}$$

The constant is readily seen to vanish by virtue of the boundary conditions at infinity. Combining (2) and (4) we have

$$\frac{v^2}{2} + \frac{\gamma}{\gamma - 1}\frac{p_\infty}{\rho_\infty}\left[\left(\frac{\rho}{\rho_\infty}\right)^{\gamma-1} - 1\right] = \frac{GM}{r}. \tag{5}$$

Equations (3) and (5) are two equations for the two variables v and ρ in terms of r, the distance from the centre of the star.

The equations may be made non-dimensional by the appropriate use of the velocity of sound in the gas at infinity, which as usual we denote by c. By the well-known formula

$$c^2 = \gamma p_\infty/\rho_\infty. \tag{6}$$

Let us introduce non-dimensional variables, x, y, z, to replace r, v, ρ, respectively, as follows:

$$\begin{aligned} r &= xGM/c^2, \\ v &= yc, \\ \rho &= z\rho_\infty. \end{aligned} \tag{7}$$

Then (3) and (5) take the non-dimensional form

$$x^2 yz = \lambda, \tag{8}$$

$$\tfrac{1}{2}y^2 + (z^{\gamma-1} - 1)/(\gamma - 1) = 1/x, \tag{9}$$

where λ is given by

$$A = 4\pi\lambda (GM)^2 c^{-3} \rho_\infty. \tag{10}$$

Accordingly λ is the non-dimensional parameter determining the accretion rate. It plays the same role as α in equation (1). It will also be observed that the relative velocity V of equation (1) has been replaced by c in (10).

3. The explicit solution of equations (8) and (9) for general γ is possible not in terms of the variables y and z but only if an auxiliary variable depending only on $y^2/z^{\gamma-1}$ is introduced. It is particularly interesting that mathematical requirements lead to the introduction of this variable, since

$$u = yz^{-(\gamma-1)/2} \tag{11}$$

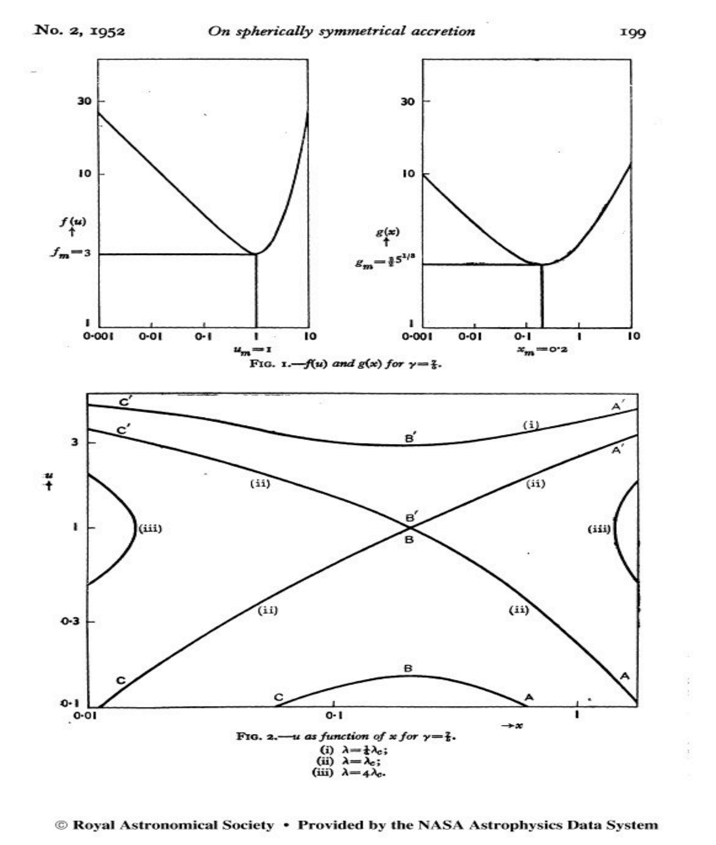

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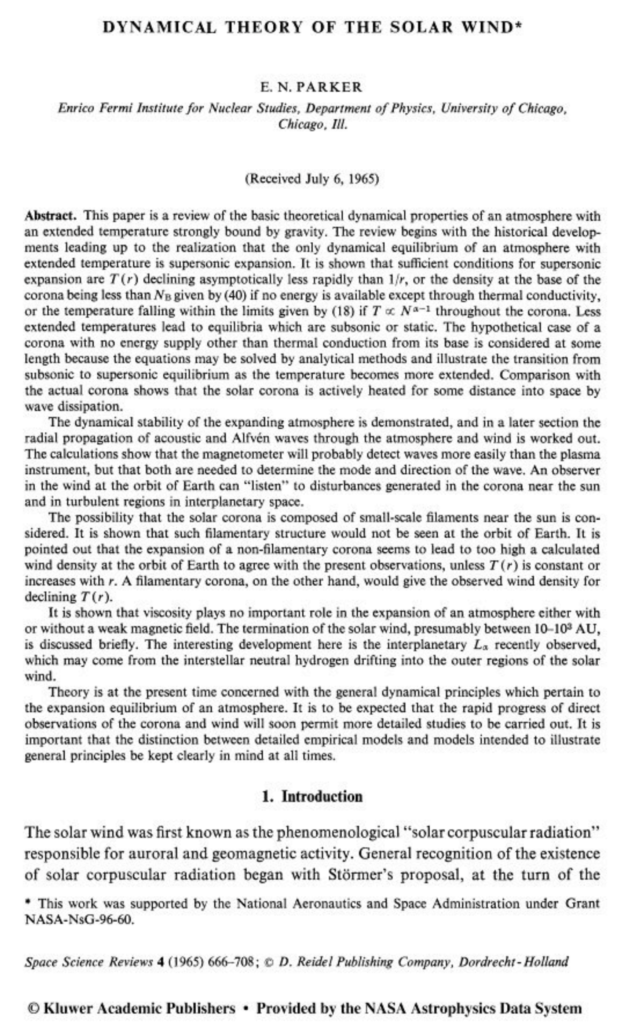
FIG. 1.—*$f(u)$ and $g(x)$ for $\gamma = \frac{7}{5}$.*

FIG. 2.—*u as function of x for $\gamma = \frac{7}{5}$.*
(i) $\lambda = \frac{1}{4}\lambda_c$;
(ii) $\lambda = \lambda_c$;
(iii) $\lambda = 4\lambda_c$.

Parker seemingly rediscovered Bondi's model later on. No references to Bondi (1952) by Parker (1958, 1965,…2007)



DYNAMICAL THEORY OF THE SOLAR WIND*

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Abstract. This paper is a review of the basic theoretical dynamical properties of an atmosphere with an extended temperature strongly bound by gravity. The review begins with the historical developments leading up to the realization that the only dynamical equilibrium of an atmosphere with extended temperature is supersonic expansion. It is shown that sufficient conditions for supersonic expansion are $T(r)$ declining asymptotically less rapidly than $1/r$, or the density at the base of the corona being less than N_B given by (40) if no energy is available except through thermal conductivity, or the temperature falling within the limits given by (18) if $T \propto N^{\alpha-1}$ throughout the corona. Less extended temperatures lead to equilibria which are subsonic or static. The hypothetical case of a corona with no energy supply other than thermal conduction from its base is considered at some length because the equations may be solved by analytical methods and illustrate the transition from subsonic to supersonic equilibrium as the temperature becomes more extended. Comparison with the actual corona shows that the solar corona is actively heated for some distance into space by wave dissipation.

The dynamical stability of the expanding atmosphere is demonstrated, and in a later section the radial propagation of acoustic and Alfvén waves through the atmosphere and wind is worked out. The calculations show that the magnetometer will probably detect waves more easily than the plasma instrument, but that both are needed to determine the mode and direction of the wave. An observer in the wind at the orbit of Earth can "listen" to disturbances generated in the corona near the sun and in turbulent regions in interplanetary space.

The possibility that the solar corona is composed of small-scale filaments near the sun is considered. It is shown that such filamentary structure would not be seen at the orbit of Earth. It is pointed out that the expansion of a non-filamentary corona seems to lead to too high a calculated wind density at the orbit of Earth to agree with the present observations, unless $T(r)$ is constant or increases with r. A filamentary corona, on the other hand, would give the observed wind density for declining $T(r)$.

It is shown that viscosity plays no important role in the expansion of an atmosphere either with or without a weak magnetic field. The termination of the solar wind, presumably between 10–10^3 AU, is discussed briefly. The interesting development here is the interplanetary L_α recently observed, which may come from the interstellar neutral hydrogen drifting into the outer regions of the solar wind.

Theory is at the present time concerned with the general dynamical principles which pertain to the expansion equilibrium of an atmosphere. It is to be expected that the rapid progress of direct observations of the corona and wind will soon permit more detailed studies to be carried out. It is important that the distinction between detailed empirical models and models intended to illustrate general principles be kept clearly in mind at all times.

1. Introduction

The solar wind was first known as the phenomenological "solar corpuscular radiation" responsible for auroral and geomagnetic activity. General recognition of the existence of solar corpuscular radiation began with Störmer's proposal, at the turn of the

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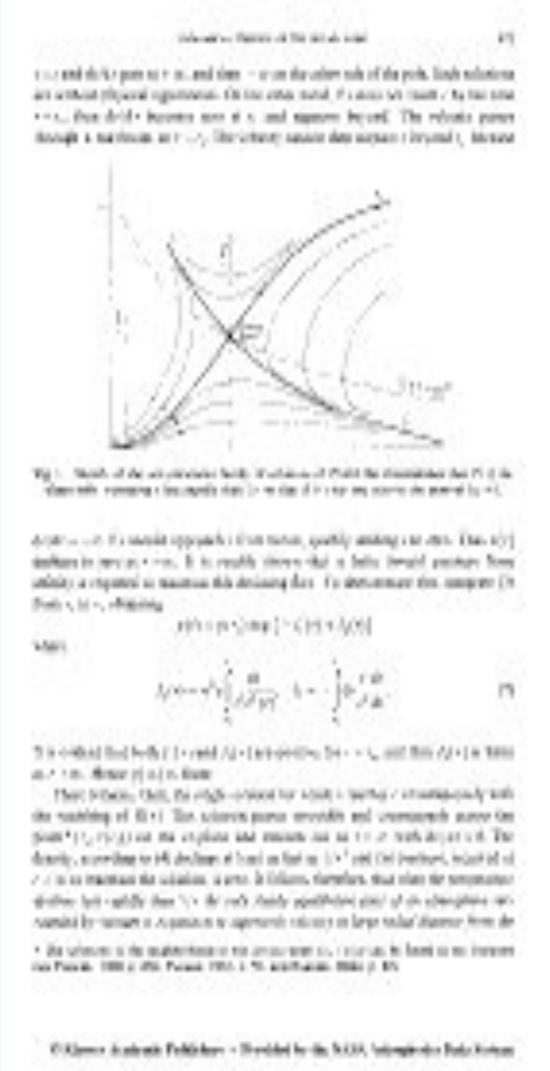
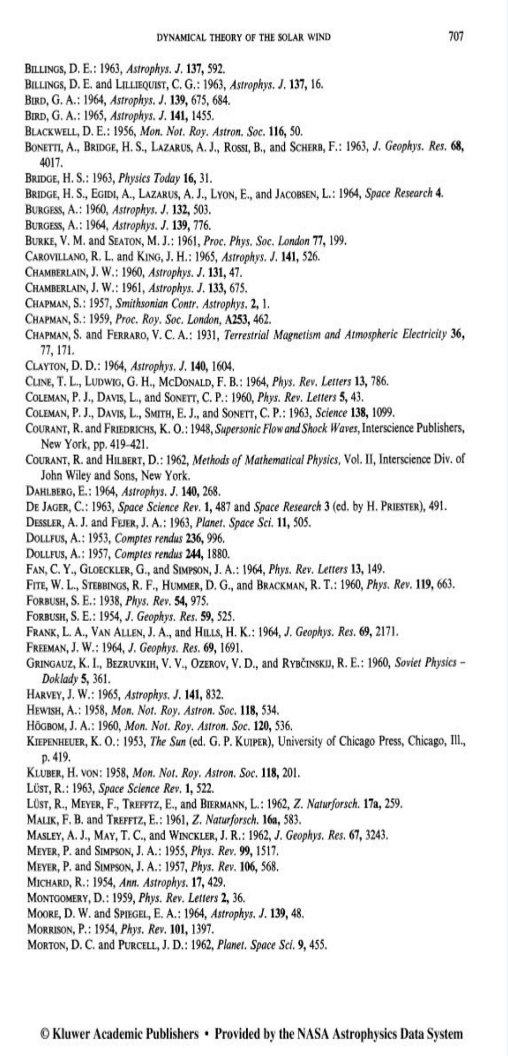




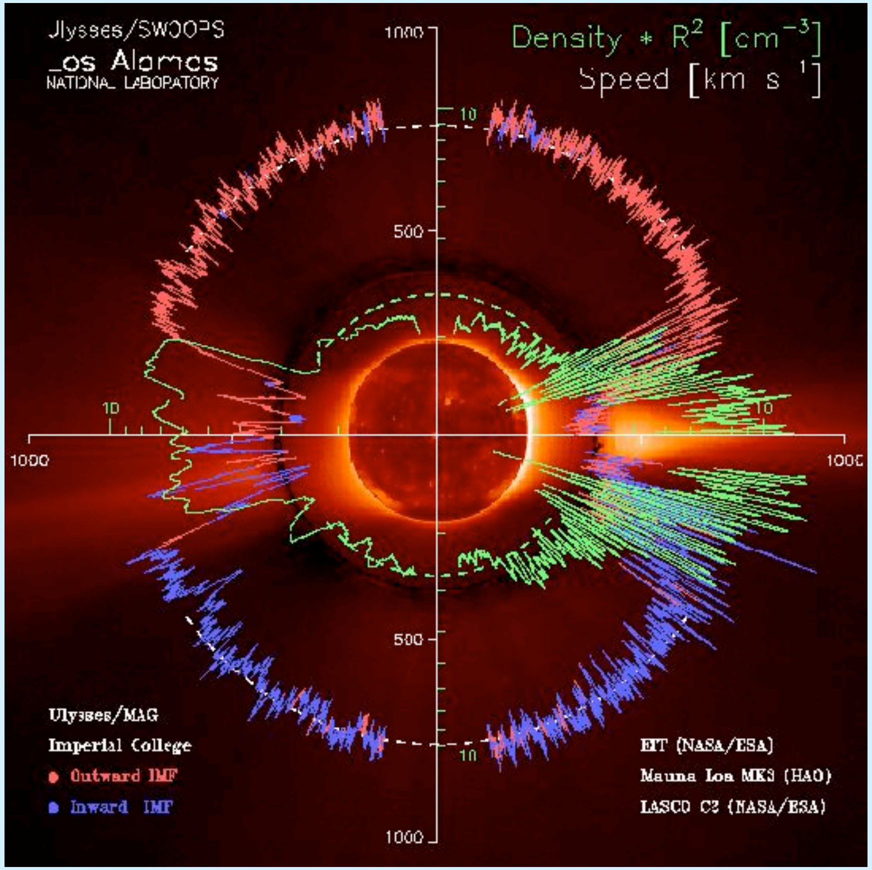
Billings, D. E.: 1963, *Astrophys. J.* **137,** 592.
Billings, D. E. and Lilliequist, C. G.: 1963, *Astrophys. J.* **137,** 16.
Bird, G. A.: 1964, *Astrophys. J.* **139,** 675, 684.
Bird, G. A.: 1965, *Astrophys. J.* **141,** 1455.
Blackwell, D. E.: 1956, *Mon. Not. Roy. Astron. Soc.* **116,** 50.
Bonetti, A., Bridge, H. S., Lazarus, A. J., Rossi, B., and Scherb, F.: 1963, *J. Geophys. Res.* **68,** 4017.
Bridge, H. S.: 1963, *Physics Today* **16,** 31.
Bridge, H. S., Egidi, A., Lazarus, A. J., Lyon, E., and Jacobsen, L.: 1964, *Space Research* **4.**
Burgess, A.: 1960, *Astrophys. J.* **132,** 503.
Burgess, A.: 1964, *Astrophys. J.* **139,** 776.
Burke, V. M. and Seaton, M. J.: 1961, *Proc. Phys. Soc. London* **77,** 199.
Carovillano, R. L. and King, J. H.: 1965, *Astrophys. J.* **141,** 526.
Chamberlain, J. W.: 1960, *Astrophys. J.* **131,** 47.
Chamberlain, J. W.: 1961, *Astrophys. J.* **133,** 675.
Chapman, S.: 1957, *Smithsonian Contr. Astrophys.* **2,** 1.
Chapman, S.: 1959, *Proc. Roy. Soc. London,* **A253,** 462.
Chapman, S. and Ferraro, V. C. A.: 1931, *Terrestrial Magnetism and Atmospheric Electricity* **36,** 77, 171.
Clayton, D. D.: 1964, *Astrophys. J.* **140,** 1604.
Cline, T. L., Ludwig, G. H., McDonald, F. B.: 1964, *Phys. Rev. Letters* **13,** 786.
Coleman, P. J., Davis, L., and Sonett, C. P.: 1960, *Phys. Rev. Letters* **5,** 43.
Coleman, P. J., Davis, L., Smith, E. J., and Sonett, C. P.: 1963, *Science* **138,** 1099.
Courant, R. and Friedrichs, K. O.: 1948, *Supersonic Flow and Shock Waves,* Interscience Publishers, New York, pp. 419–421.
Courant, R. and Hilbert, D.: 1962, *Methods of Mathematical Physics,* Vol. II, Interscience Div. of John Wiley and Sons, New York.
Dahlberg, E.: 1964, *Astrophys. J.* **140,** 268.
De Jager, C.: 1963, *Space Science Rev.* **1,** 487 and *Space Research* **3** (ed. by H. Priester), 491.
Dessler, A. J. and Fejer, J. A.: 1963, *Planet. Space Sci.* **11,** 505.
Dollfus, A.: 1953, *Comptes rendus* **236,** 996.
Dollfus, A.: 1957, *Comptes rendus* **244,** 1880.
Fan, C. Y., Gloeckler, G., and Simpson, J. A.: 1964, *Phys. Rev. Letters* **13,** 149.
Fite, W. L., Stebbings, R. F., Hummer, D. G., and Brackman, R. T.: 1960, *Phys. Rev.* **119,** 663.
Forbush, S. E.: 1938, *Phys. Rev.* **54,** 975.
Forbush, S. E.: 1954, *J. Geophys. Res.* **59,** 525.
Frank, L. A., Van Allen, J. A., and Hills, H. K.: 1964, *J. Geophys. Res.* **69,** 2171.
Freeman, J. W.: 1964, *J. Geophys. Res.* **69,** 1691.
Gringauz, K. I., Bezruvkih, V. V., Ozerov, V. D., and Rybčinskij, R. E.: 1960, *Soviet Physics – Doklady* **5,** 361.
Harvey, J. W.: 1965, *Astrophys. J.* **141,** 832.
Hewish, A.: 1958, *Mon. Not. Roy. Astron. Soc.* **118,** 534.
Högbom, J. A.: 1960, *Mon. Not. Roy. Astron. Soc.* **120,** 536.
Kiepenheuer, K. O.: 1953, *The Sun* (ed. G. P. Kuiper), University of Chicago Press, Chicago, Ill., p. 419.
Kluber, H. von: 1958, *Mon. Not. Roy. Astron. Soc.* **118,** 201.
Lüst, R.: 1963, *Space Science Rev.* **1,** 522.
Lüst, R., Meyer, F., Trefftz, E., and Biermann, L.: 1962, *Z. Naturforsch.* **17a,** 259.
Malik, F. B. and Trefftz, E.: 1961, *Z. Naturforsch.* **16a,** 583.
Masley, A. J., May, T. C., and Winckler, J. R.: 1962, *J. Geophys. Res.* **67,** 3243.
Meyer, P. and Simpson, J. A.: 1955, *Phys. Rev.* **99,** 1517.
Meyer, P. and Simpson, J. A.: 1957, *Phys. Rev.* **106,** 568.
Michard, R.: 1954, *Ann. Astrophys.* **17,** 429.
Montgomery, D.: 1959, *Phys. Rev. Letters* **2,** 36.
Moore, D. W. and Spiegel, E. A.: 1964, *Astrophys. J.* **139,** 48.
Morrison, P.: 1954, *Phys. Rev.* **101,** 1397.
Morton, D. C. and Purcell, J. D.: 1962, *Planet. Space Sci.* **9,** 455.

Solar Wind Origins:
Modern Status of the Problem

- The analysis performed by Bondi (1952) was repeated by Parker in 1958 with the conclusion: **wind**.
- Bernoulli equation does not indicate the direction of flow.
- Initial or boundary conditions are decisive.

Solar wind origin problem

- Two aspects, two main questions, both are unsolved.
- **First**, astrophysical question: why wind and not accretion? Tentative answer: because of evolutionary stage after the Hayashi phase (gravity and contraction) or the thermonuclear burning. **Global view**, Sun as a dot. Status: several works only. Not clear.
- **Second**, plasma physics and electrodynamics question: What are space-time structures and processes leading to the continuous super magnetosonic outflow from the Sun. **Local view,** parts of the Sun**.** Status: many hundreds of papers. All needed general physics is clear and established, but the puzzle and mosaic remains. Not clear.
- Both aspects are interrelated and coupled by nonlinear and non-local links.


Ulysses/SWOOPS
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Density * R^2 [cm^{-3}]
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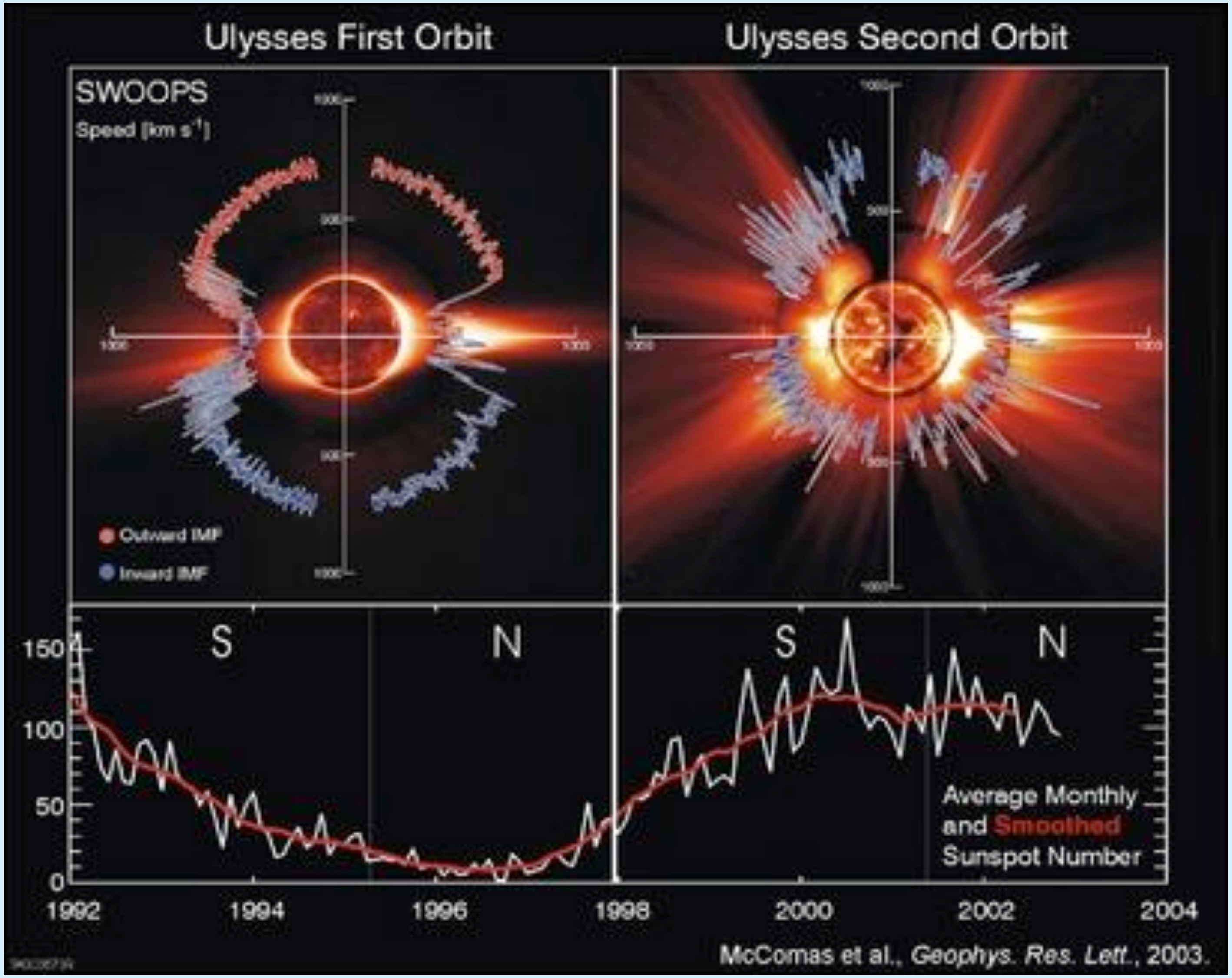
Mauna Loa MK3 (HAO)
LASCO C2 (NASA/ESA)



McComas et al., *Geophys. Res. Lett.*, 2003.

Date: 04 Jul 2003
Satellite: Ulysses
Depicts: SWOOPS solar wind plots
Copyright: D. McComas

Polar plots of solar wind speed as a function of latitude for Ulysses' first two orbits. The solar wind speed data was obtained by the SWOOPS instrument (Solar Wind Observations Over the Poles of the Sun). The bottom panel shows the sunspot number over the period 1992-2003. The first orbit occurred through the solar cycle declining phase and minimum while the second orbit spanned solar maximum.

Both solar wind plots are plotted over solar images characteristic of solar minimum (17 August 1996) and maximum (7 December 2000). The solar images are composites of (from the center out): the Solar and Heliospheric Observatory (SOHO) Extreme ultraviolet Imaging Telescope (Fe XII at 195 Å), the Mauna Loa K-coronameter (700–950 nm), and the SOHO C2 Large Angle Spectrometric Coronagraph (white light).

Short resume (1)

- Turbulent and laminar transports of energy, momentum and mass in the hot solar corona and at the cooler transition region/ chromospheric levels of the solar atmosphere finally result in the permanent, but strongly variable supermagnetosonic plasma outflow from the Sun: the solar wind. **This view differs from past laminar theories of the coronal heating and the solar wind formation.**

Short resume (2)

- Many important aspects of this general astrophysical and plasma physical phenomenon are known due to numerous spacecraft measurements, as well as various remote sensing methods. In spite of rapidly increasing information and knowledge, there is no sufficiently deep physical understanding of the connection between observed phenomena, structures and parameters on the Sun and measured properties of the solar wind in the heliosphere.

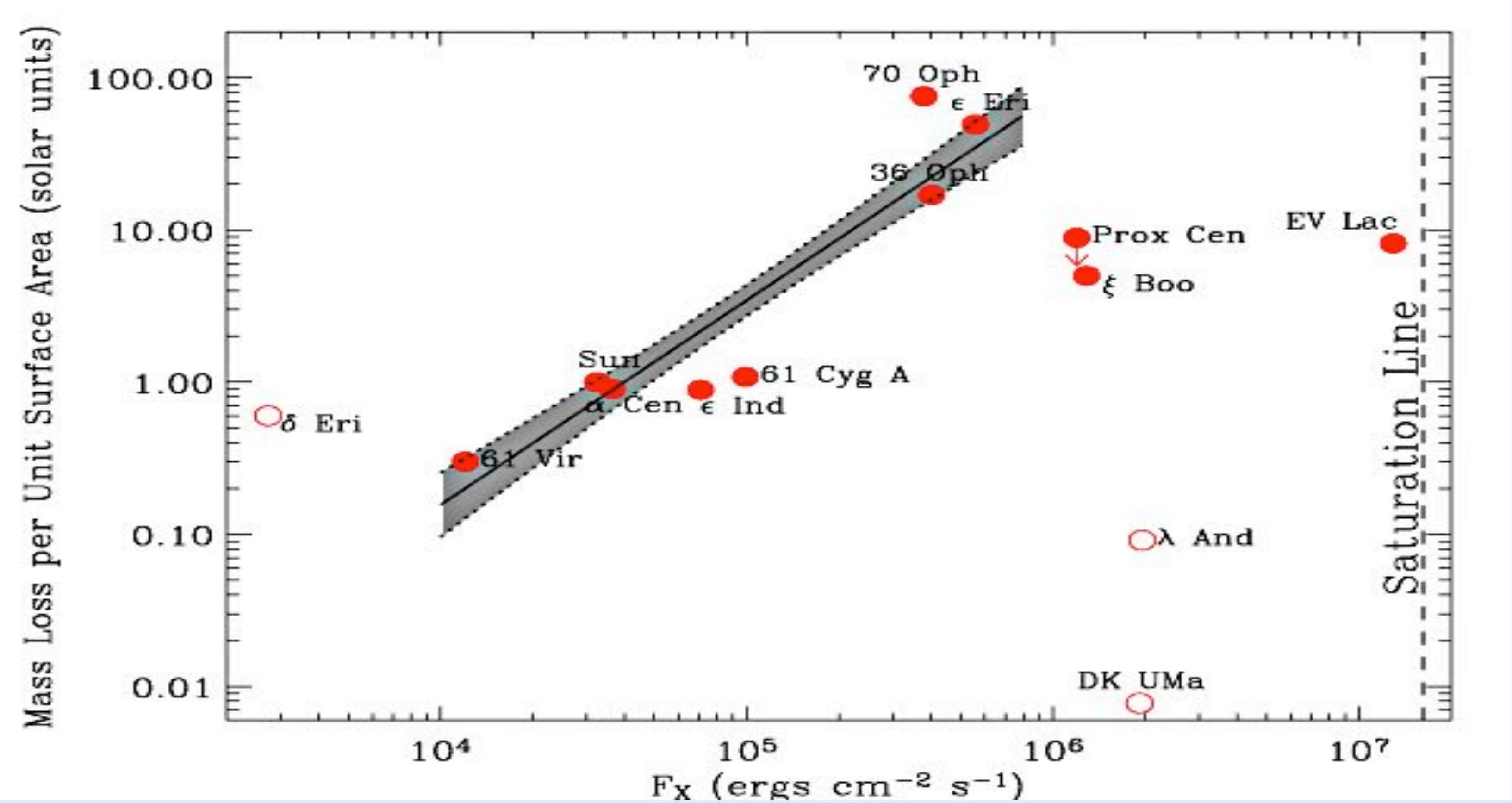
Three important aspects

- There are three important aspects of the solar wind origins problem that we are aimed to focus on:
- 1) overall and global solar wind flow as a stellar phenomenon;
- 2) large-scale and long-term quasi-stationary structure;
- 3) small-scale and transient self-organization.
- All three aspects are mutually related by complicated non-linear couplings, which are not well investigated and described.

Solar wind as a result of the stellar evolution

- The Solar System and the Sun formation processes, according to modern cosmogenic hypotheses, started as an accretion from the local interstellar gas-dust medium mediated by electromagnetic fields and radiation.
- Open questions: when and how the accretion was stopped and replaced by the plasma outflow from the Sun?

Measured mass loss rates (per unit surface area) plotted versus X-ray surface flux (Wood et al., 2005a).
The filled and open circles are main sequence and evolved stars, respectively. For the main sequence stars with , mass loss appears to increase with coronal activity, so a power law has been fitted to these stars and the shaded region is the estimated uncertainty in the fit.
The saturation line represents the maximum



Bondi’s model consideration

- The model of the steady state spherically symmetric flows of the politrope gas in the gravity field of the central star body was first developed by Bondi (1952). He obtained and investigated the whole family of subsonic, transsonic and supersonic solutions of the reduced Bernoulli equation.
- The same family of Bernoulli equation solutions was used for the description of possible inflows to the Sun - accretion (Bondi, 1952) and outflows - solar wind (Parker, 1958).
- Dilemma. The selection between positive or negative branches for the radial velocity can be not uniquely decided in the framework of this steady state approach without additional hypotheses about external boundary conditions in the interstellar medium and internal conditions on the Sun. Physical analogy: electrons and positrons in the field theory.
- Mixed and intermittent accretion and wind regimes are easily reproduced by the same Bondi model. Transitions between those regimes are not excluded and possible.

Entropy considerations

- Not helpful to resolve the ‘accretion-wind’ dilemma.
- It is because of physically open system including given star and its surroundings should be considered.
- Entropy increases in closed physical systems, but it could locally decrease.

Evolution considerations

- Evolving interstellar medium with stars.
- Physically open system with energy, momentum and mass flows.
- Prehistory and memory of past development bring initial conditions, which are not known a priori from direct observations and could be only speculated.
- Time dependence and ‘world line’ can be followed and constructed for future development only within some accuracy. Predictability horizon exists, but not known.
- Memory is partially lost due to dissipation. Sufficiently deep past history is not reproducible in principle because of lost information via radiation and mass losses from the finite volume under consideration.

Momentum conservation

- Rotation of the hypothetical cool (~ 10 K) proto-solar cloud.
- Star activity related to differential rotation.
- Non – rotating solar type star: what about its activity? Does sunspots and cycles exist?
- What is the role of planets?
- Examples of stars with a solar type activity, but without planets. Known or not?

General comments

- Only finite volumes and limited time intervals are tractable in physics.
- ‘Universe as a whole’ is not a subject for physical considerations because it is not based on necessary and sufficient input information from observations.
- Knowledge is limited and will remain limited, though increasing.

Preliminary conclusions from general and evolutionary considerations in application to the solar wind origin problem

- Attempts to solve the solar wind problem as the unique situation for stars with a hot corona in a tenuous interstellar medium are physically not tenable.
- Two possible branches – wind and accretion are admissible for the stars of the solar type.
- The selection between two branches is due to evolutionary path, but not to the structure of the stellar interiors.
- The dilemma wind/accretion de facto has one and only one evolutionary solution.

Stars as donors and acceptors of the interstellar gas

- The current situation in the star - interstellar gas interaction depends on many parameters of a star under consideration and surrounding medium including neighbour stars.
- If the evolutionary paths are different, stars can serve as donors or acceptors.
- Local solution is impossible for dilemma ‘wind/accretion’.

Turbosphere around the Sun

- Up-and -down flows. Lateral motions of plasma.
- Transient (S<<1) and quasi steady (S>>1) regimes.
- Subsonic M<<1, trans-sonic M~1 and super magnetosonic M>>1 cases. M here stays for $M_{S,\ ,}M_A$ or their combinations (slow and fast magnetosonic speeds).
- Spicules, macrospicules, jets, eruptions demonstrate confined (finite) and infinite trajectories of moving particles in the chromosphere and the corona.
- Solar wind originates as a tiny regular outflow superimposed on the background of more powerful irregular (turbulent) motions. Some of these motions are inbound and returning to the Sun, but outbound motions dominate more and more with distance from the surface.
- Illustrations are on the next slides.

Turbopause around the Sun

- Definition.
- Turbopause is the instant surface where the local turbulent velocity (Vturb) is approximately equal to the average and regular speed of the radial plasma outflow V.
- Below the turbopause: Vturb > V .
- Above the turbopause: V > Vturb.

Conservation Laws

mass

momentum

energy

Governing MHD equations with dissipation and radiation

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0, \qquad (1)$$

$$\rho\{\frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v}\} + \vec{\nabla} p - \frac{1}{4\pi}[[\vec{\nabla} \times \vec{B}] \times \vec{B}] + \qquad (2)$$

$$+ \vec{F}_{viscous} + \vec{F}_{gravity} = 0$$

$$\frac{\partial}{\partial_t}(\rho_u + \frac{1}{2}\rho_{v^2}) + \frac{\partial}{\partial_{x_i}}(\rho_{v_i} w + \rho_{v_i}\frac{v^2}{2} + \rho_{v_k}\sigma'_{ik} - \kappa\frac{\partial T}{\partial_{x_i}} +$$

$$+ \frac{1}{4\pi} e_{ikl} e_{lmn} v_m B_k B_n + \frac{c}{4\pi\sigma} e_{ikl} j_k B_l) = -L + A$$

Symbolic shape of equations

$$\frac{\partial \rho}{\partial t} + \vec{\nabla}(\rho \vec{v}) = 0 , \qquad (4)$$

$$S^{-1} \quad + \quad 1$$

$$\rho \{ \frac{\partial \vec{v}}{\partial t} + (\vec{v}\vec{\nabla})\vec{v} \} = -\vec{\nabla} p + \frac{1}{4\pi} [[\vec{\nabla} \times \vec{B}] \times \vec{B}] + \qquad (5)$$

$$+ \vec{F}_{viscous} + \vec{F}_{gravity}$$

$$S^{-1} \quad + \quad 1 \quad - \quad M^{-2} \quad + \quad M_A^{-2} \quad + \quad \mathrm{Re}^{-1} \quad + \quad Fr^{-!}$$

$$\frac{\partial}{\partial t}(\rho u + \frac{1}{2}\rho v^2) + \frac{\partial}{\partial x_i}(\rho v_i w + \rho v_i \frac{v^2}{2} + \rho v_k \sigma'_{ik} - \kappa \frac{\partial T}{\partial x_i} +$$

$$+ \frac{1}{4\pi} e_{ikl} e_{lmn} v_m B_k B_n + \frac{c}{4\pi\sigma} e_{ikl} j_k B_l) = -L + A$$

$$M^{-2} S^{-1} \quad + \quad S^{-1} \quad + \quad M^{-2} \quad + \quad 1 \quad + \quad \mathrm{Re}^{-1} \quad + \quad \mathrm{Re}^{-1} M^{-2} \mathrm{Pr}^{-1}$$

$$+ \quad M_A^{-!} \quad + \quad M_A^{-2} \mathrm{Re}_m^{-1} \quad - \quad V_e \quad + \quad Fr^{-1}$$

Dimensionless parameters

Name	Description	Role
Strouhal	Time / Flight times	Time scales
Knudsen	Mean free path / Size	Length scales
Velocity-emission	Kinetic energy / EM emission	Plasma density
Mach	Bulk speed / Thermal speed	Temperature
Magnetic Mach	Bulk speed / Alfvén speed	Magnetic field
Froude	Velocity / Free escape speed	Gravity
Faraday	Potential / Inductive	Electric field
Trieste numbers	Inflows / Inner flows	Openness degrees

Table 3. Irreducible and full set of independent orthogonal dimensionless parameters in the ‘velocity normalised basis’

Symbol	Name	Formula / Definition	Signifiance
	Magnetic Mach (Mach – Alfvén)		Magnetic field and currents
	Trieste numbers (set)	Ratio of internal and boundary crossing fluxes $\left(\frac{E_{kin}}{E_{at}}\right)\left(\frac{x}{v\tau_{rad}}\right)$	Openness degree of the object against energy, momentum and mass fluxes

Strouhal number

- S ~ vt/L **non-invariant, reference frame dependent parameter**
- S>>1 quasi-stationary flow (asymptotically large S values mean steady state)
- S<<1 transient flow
- S~1 intermediate regime (for example, linear waves or small convective perturbations)

Strouhal number (ctnd)

- S ~ Vt/L
- Quiescent prominences:
- L~ 10^5 km, V~ 1 km/s, t~ 10^6 s (many days, a month) (life time)
- Hence, S ~ 10
- Looks like quasi-steady flows during life time

Strouhal number (ctnd)

- $S \sim vt/L$
- Eruptive prominences: for example,
- $L \sim 10^5$ km, $V \sim 100$ km/s, $t \sim 1$ hour
- Looks like transient phenomenon

Laminar? Turbulent?

- Number of degrees of freedom N involved in process under consideration
- Laminar   if N~ 1 “simple”
- Turbulent if N>>1 “complicated”
- Reynolds number Re is not invariant for this purpose (reference frame dependent impressions of flow). Because of this,
- Re >1, Re <1 is not a good classification.

Dimensionless Faraday number F

- Ratio of inductive and potential electric fields
- **F~ (j/ρc) (L/ct)**

where

j - electric current density

ρ - electric charge density

L - length

c - velocity of light

t - time

F>>1 inductive fields dominate

F<<1 Coulomb fields dominate → electrostatics **important!**

Applications: thermonuclear fusion problem, double layers on the Sun

Trieste numbers T

- Set of dimensionless parameters: ratios of energy, momentum , mass fluxes inside, outside and across the volume boundaries
- T>>1 open system
- T<<1 closed system
- T~1 intermediate case
- **Important example:** quiescent prominence – open system with mass flows through it (siphon flows in loops from one foot point to opposite foot point, blue and red shifts in legs). It is not a magneto-static equilibrium (as generally believed) but a quasi-steady or non-steady state with flows

Why solar flares and CMEs originate?

- It is because of subphotospheric free energy supply in the same, larger and smaller space-time scales: T~1, T>>1, T<<1.
- All these regimes involved in preparation and development
- They are non-linearly coupled

- Information and ‘signals’ from interior of the Sun are needed to predict solar flares and CMEs

Ve number (on the Sun)

- Ratio of the energy losses via solar wind to the losses due to electromagnetic radiation of the corona
- Averages on time :
- Ve>>1 in coronal holes (dark regions, fast wind)
- Ve<<1 in active regions (bright loops, slow motions)
- Ve~1 intermediate value in quiet corona

Ve number (continued)

- Ve>>1 in coronal mass ejections (CMEs) – high loop eruptions, prominences, arcades
- Ve<<1 in solar flares – low loops, brightening, confined motions
- Ve~1 intermediate case - both
- Typically CMEs and flares are accompanying each other in different proportions from CME-like to flare like situations
- Flares/CMEs: No cause/consequence relations, but parallel energy release channels from the same free energy sources

CONCLUSIONS

- ✓ The **solar wind origin problem** has only one evolutionary solution. Suggested answers to the main questions:
- ✓ 1) Why the solar wind blows? **Because of the present evolution stage of the Sun and the lack of equilibrium on the Sun.**
- ✓ Suggested approach to a deeper understanding: time dependent models of the evolution of the Sun with its surroundings.
- ✓ 2) How the solar wind plasma accelerated and heated? **In many different ways. Electric currents in the corona are main drivers of the heating and acceleration of the palsma.**
- ✓ Suggested approach to deeper answer: please investigate numerous MHD and kinetic regimes and compare them with available and new measurements and observations.
- ✓ **Thank you!**