# PHLEGETHON FLOW - A PROPOSED ORIGIN FOR SPICULES AND CORONAL HEATING

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## INTRODUCTION

We draw upon existing work to put together a model of the mass, energy and magnetic field transport into the corona. This transport originates, in our model, from a deep-seated flow issuing out of concentrated field structures. The fluid is ejected into the solar atmosphere with the help of magnetic forces on fibril field structures. We refer to the subsurface flow as a "phlegethon", named after the river of fire that flowed in Hades in Greek mythology. A new term to describe the gas is suggested because the flow appears to carry significantly greater amounts of energy in its non-potential magnetic fields than in its kinetic energy. As fire is a process which unleashes the stored (chemical) energy to create heat, the term is used here generically to describe heating through the unleashing of a magnetic form of stored energy. As with other models, the wave and current energy flux leads to the dramatic heating of the solar atmosphere. We shall concentrate on the flow below the photosphere (the phlegethon flow), which allows the energy to pass into, and be dissipated within, the solar atmosphere. We do not treat the details of the physical processes (wave breaking, heat conduction, etc.) above the photosphere, nor on the coronal field geometry, which usually forms loops in the solar atmosphere.

Network field structures are already considered good candidates for supplying coronal mass as they carry plasma jets, known as spicules (e.g., Beckers, 1972), having densities from $3 \times 10^{10}$ to $3 \times 10^{11}$ particles cm$^{-3}$ (compared to $\sim 10^{8}$ particles cm$^{-3}$ in the surrounding corona), with diameters of 500 to 1200 km, extending in height 10,000 to 20,000 km, with temperatures from 1 to $2 \times 10^{4}$ K. They contain material with upward supersonic flow velocities of 20 to 30 km s$^{-1}$ with neither sign of material falling nor the upward velocity abated by gravity, make them ideal for supplying coronal material (Withbroe and Noyes, 1977). Thus we consider these structures as sources of material and energy for the solar atmosphere. A number of reviews have been written on the nature of spicules, with Beckers (1972) providing a comprehensive review of their observational and theoretical understanding.

## THE ORIGIN OF SPICULES

We consider spicules to represent highly evacuated flux tubes from which gases pour supersonically into the solar atmosphere. Observationally, the high degree of evacuation of fluxtubes may manifest itself in the large nearly uniform field strength of 1400-2000 Gauss (Beckers and Schroter, 1968), comparable to the photospheric gas pressure, observed in nearly all photospheric magnetic features. This leaves little room for significant gas pressure on these field structures. Parker (1984) discusses theoretical reasons how in a superadiabatic environment, free energy is utilized to concentrate the magnetic field into localized bundles of large field strength (fibrils), consistent with evacuated fluxtubes.

The differing behavior of magnetic buoyancy from gaseous buoyancy may play a major role in the evacuation of fluxtubes, since buoyancy is a critical force for the fluid dynamics within the convection zone. Buoyancy is required for this material to overturn since there is insufficient thermal energy ($4 \times 10^{-10}$ ergs per hydrogen ion) without buoyancy to allow the bulk of the material to rise from the convection zone base to the photosphere against the gravitational potential ($-2 \times 10^{-9}$ ergs per hydrogen ion). The magnetic buoyancy force differs from the thermal buoyancy force, because the latter is proportional to the weight of the displaced material and is therefore comparable to the actual weight of the material within a specific volume. The magnetic buoyancy force, however, originates from the non-potential field configuration, which the surrounding fluid pressures have contorted the magnetic field into. This bears little relation to the weight of material on the magnetic field, but rather is related to the external fluid pressures, modified by the Maxwell stress tensor. We envision a fibril fluxtube extending down to the base of the convection zone, decreasing in radius as it is examined at greater depths. At the lowest altitudes the magnetic field will no longer contract indefinitely, so that at some altitude the magnetic field lines will be nearly parallel. At these altitudes the magnetic buoyancy force will be much less than the gravitational or thermal buoyancy force. In the unmagnetized convection zone fluid, the buoyancy force balances the gravity force since the equations of stellar structure relate the gravitational force to the pressure gradient. Thus the gas density within a deep seated fluxtube decreases with altitude faster than the surrounding gas, where the thermally buoyant forces operate, and the fluxtube can achieve a relatively low density during its passage to the solar surface. Examining conditions higher in the convection zone, near the photosphere, for example, the magnetic stresses are near $10^{-2}$ dynes $\mathrm{cm}^{-3}$ for 300 km wide fibrils of field strength 2000 Gauss, with a 300 km scale height. This is comparable to the gravitational force of $10^{-2}$ dynes $\mathrm{cm}^{-3}$ for photospheric densities of $2 \times 10^{17}$ particles $\mathrm{cm}^{-3}$.

To summarize our view, for typical deep convection zone densities and fields, gravitational or buoyancy forces exceed magnetic forces for field aligned fluid flow. For shallow conditions or highly evacuated fluxtubes, the Maxwell stresses can exceed the gravitational force. This also can occur at any height, given a sufficiently low density on the fluxtube, because the Lorentz force is governed by the field geometry, not by the amount of material on the fluxtube. Thus, near the solar surface the vertical Lorentz force per unit mass is comparable to, or can exceed the gravitational or buoyant force. This can allow the high flow velocities observed in spicules to occur as a "solar wind" type solution to the Bernoulli equations including the Lorentz force.

## ATMOSPHERIC HEATING AND ACCELERATION

We shall examine a treatment following the work of Bailyn et al.(1985). They have considered the solution topologies for polytropic winds associated with momentum deposition and find the general solution can have multiple critical points. Nevertheless, an integral of the motion can be obtained from the magnetic Bernoulli equation as:

$$KE_p \equiv \tfrac{1}{2}v^2+c_o^2 \ln\left(\frac{\rho}{\rho_o}\right)=E+\int_{r_o}^{r} D(r')dr' - \Phi_G \qquad (1)$$

where E is the constant of integration (which without the magnetic stress term would be the total energy per particle), $D(r) \equiv L_z/\rho = L_z/Nm$ is the rate of non-thermal momentum addition per unit mass; $c_o^2 \equiv \gamma P/\rho$, the square of the sound speed; $KE_p$, the kinetic energy per particle; $\Phi_G$, the gravitational potential; and where $E_B=\int_r^r D(r')\,dr'$ may be calculated for a known magnetic field and density structure, including the wave field.

Now examining the terms of equation (1), for the spicule flow we have $\frac{1}{2}v^2 \sim 2 \times 10^{12}$ $cm^2\ s^{-2}$, and $c_o^2 \simeq 10^{12}$ $cm^2\ s^{-2}$, both small compared with $\Phi_G \simeq 10^{15}$ $cm^2\ s^{-2}$, and $E_B \simeq 10^{14}$ $cm^2\ s^{-2}$ for 10 Gauss twisted fields containing $10^{11}$ particles $cm^{-3}$ integrated over a 1000 km height. Thus for spicule material a small distance above the photosphere, the terms on the left of equation (1) may be small, and the terms on the right, between $10^{14}$ and $10^{15}$ $cm^2\ s^{-2}$. Figure 1 shows these terms in the solar atmosphere for a simple field geometry.

The Maxwell stress, $L_z$ includes not only the static component which cannot provide heating, but also contributions from waves (in particular, their decay). If we consider a small volume of space containing an arbitrary collection of Alfven waves, one solution to the dynamical equations, as Parker showed, is for the plasma to travel along the field lines at the Alfven speed. In this case the waves (in this reference frame) can remain stationary. Thus we can consider a damped set of waves travelling into a region of space, to add energy and momentum to the plasma within. A solution in which the plasma flow velocity equals the Alfven velocity, we refer to as the "equipartition solution". For sinusoidal waves, the energy transport is divided equally between mechanical and electromagnetic terms. Above the photosphere, the magnetic contribution (per unit mass) to the vertical momentum equation, $E_B$, monotonically rises, until it exceeds all other physical contributors (eg. $\Phi_G$). The flow gradually accedes to the demands of this relentless magnetic force, until the flow rate approaches the local Alfven velocity. This occurs at the "equipartition solution", when the wave energy and particle energy are comparable. At this point, the coronal plasma can no longer acquire energy or momentum from the waves (the curve $KE_p$ approaches an asymptotic value) in the same manner that a sailboat "running with the wind" cannot surpass the wind speed.

Coronal heating problems are now considered. Kuperus, Ionson, and Spicer (1981) suggest that the quiet corona requires a heat source of about $3 \times 10^5$ erg $cm^{-2}\ s^{-1}$ and the quiet chromosphere, a heat source of $4 \times 10^6$ erg $cm^{-2}\ s^{-1}$ for global values of $2 \times 10^{28}$ erg $s^{-1}$ and $2.4 \times 10^{29}$ erg $s^{-1}$, respectively. The Maxwell stress may be transported at a flow rate of $S \approx V_A\ (B_oB_1/4\pi)$. Taking spicule number densities at $10^{11}$ $cm^{-3}$, field strengths of $B_o \approx B_1 \approx 10$ G, we have $V_A$ of order 100 km $s^{-1}$, yielding an energy flux of $S \approx 10^8$ erg $cm^{-2}\ s^{-1}$, providing for a global value of $2 \times 10^{28}$ ergs $s^{-1}$, when integrated over phlegethon structures with a total area of $2 \times 10^{20}$ $cm^2$. This value is sufficient for coronal heating, but 10 times too low for chromospheric heating. These flow energies appear also sufficient, when

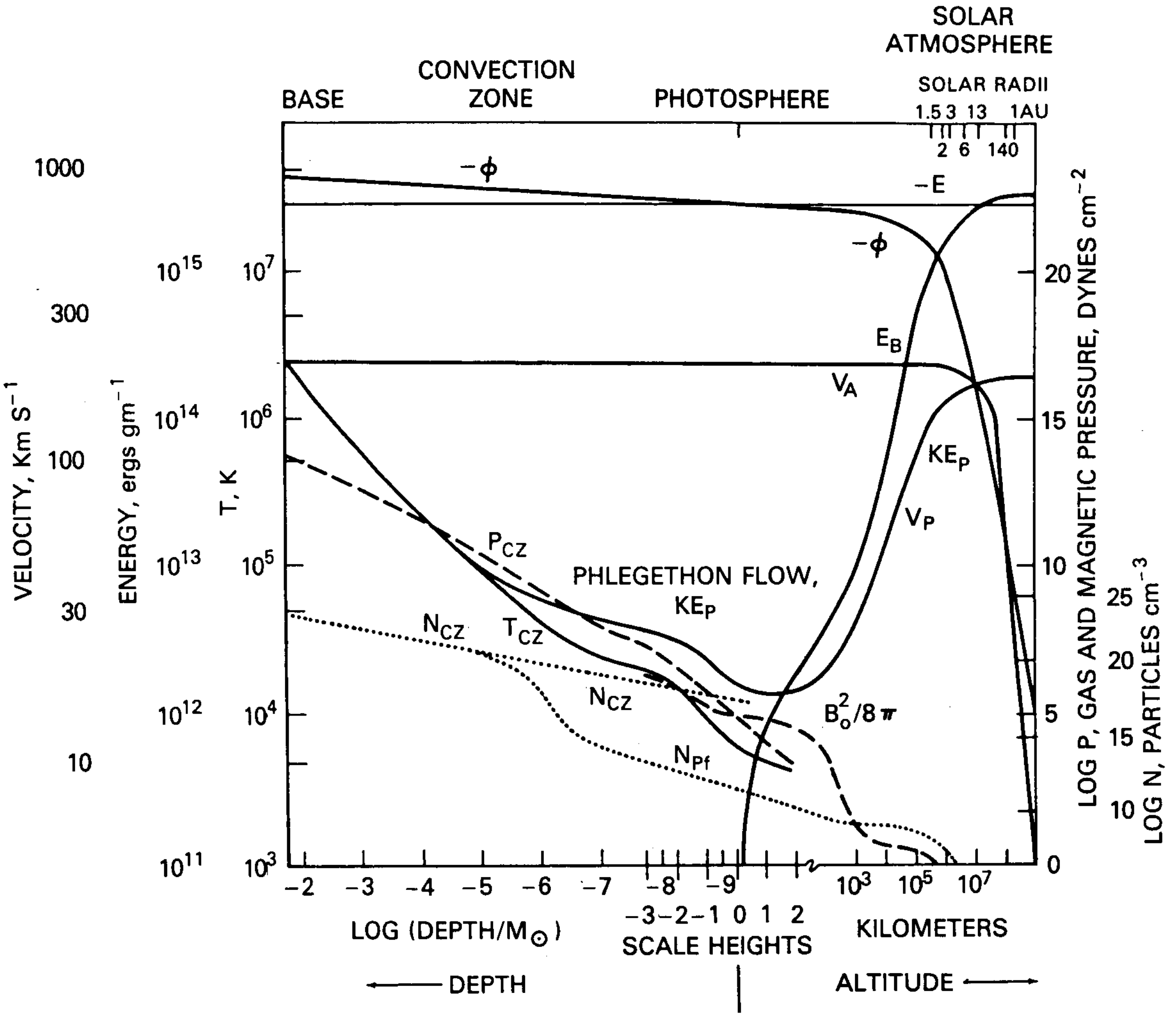

Figure 1. Shown are pressures, energies and densities in the convection zone and solar atmosphere. The subscript cz refers to normal convection zone fluid, and pf to "phlegethon flow" - material flow embedded on field structures. The magnetic pressure exceeds gas pressure above the photosphere. The kinetic energy per particle KE$_p$ related to the temperature and flow speed squared, the magnetic contribution to the flow energy, E$_B$, the constant, E, of the motion, and gravitational potential, $\Phi$, on fluxtubes are also provided in the convection zone and solar atmosphere. The Alfven velocity, V$_A$, allows the base energy quality to reach the solar atmosphere. To allow for the rapidly changing conditions near the photosphere, doubly logarithmic abscissa scales are chosen which provide magnification within the region.

thermalized, to elevate spicule material to coronal temperatures. As the waves "break", they contain an energy flux of S and a mass flux of $NV_F$. Dividing the former by the latter provides for $5 \times 10^{-10}$ ergs $\text{particle}^{-1}$, or $\sim 2 \times 10^6$ K thermal energy per particle.

## DISCUSSION

We have examined the following scenario for solar atmospheric heating. Fluid on rising fluxtubes deep within the convection zone obtains insufficient buoyancy to rise en masse to the photosphere. In this fashion, rising fluxtubes within the Sun's convection zone can become highly evacuated. Near the photosphere, the magnetic buoyancy force becomes large, ejecting material upwards in accordance with the magnetic Bernoulli equation. This leads to an outpouring of supersonic gases into the solar atmosphere. These gases contain insufficient kinetic energy to heat the corona or escape the gravitational pull of the Sun. In our view they are "wicked" into the solar atmosphere, where an energization of the material by concurrent wave field stresses occurs.

Examining these gases as they ascend on fluxtubes to greater altitudes, their density decreases, owing to gravity and the widening field channel that these gases flow along. On typical field geometries, when the fluid velocity exceeds a few km $s^{-1}$, hydromagnetic waves dominate the vertical momentum equation, relative to gravity ($L_z > \rho g$). This allows for the velocity to increase rather than decrease with altitude, consistent with the observed behavior of spicules rising supersonically into the solar atmosphere, with their motion unabated by gravity. Although the gases contain insufficient kinetic energy to supply coronal heating, they carry concurrent Maxwell stress and wave energy in their non-potential field configuration. With the explosive release of this energy, the gases erupt into the solar atmosphere to form a hot corona and a dynamically expanding wind. We find that these structures can provide the magnetic field, mass flow, and energy budget necessary to maintain the conventional solar atmosphere. Within the framework of this model, energy may dissipate at a temperature comparable to the temperature where the waves originated, allowing for an "equipartition solution" of atmospheric flow, departing the Sun at velocities approaching the maximum Alfven speed.

## REFERENCES

Bailyn, C., Rosner, R. and Tsinganos, K., 1985, Ap. J., 296, 696.
Beckers, J. M., 1972, Ann. Rev. Astron. Astrophys., 73.
Beckers, J. M. and Schroter E. H., 1968, Solar Phys., 4, 142.
Kuperus, M., Ionson, J. A., and Spicer, D. S. 1981, Ann. Rev. Astron. Astrophys., 19, 7.
Landau, L. D., 1951, Classical Theory of Fields, (Addison-Wesley Reading, Mass.).
Parker, E. N. 1984, Ap. J., 283, 343.
Withbroe, G. L. and Noyes, R. W. 1977, Ann. Rev. Astron. Astrophys., 15, 363.