SMALL-SCALE UNRESOLVED SOLAR MAGNETIC FIELDS

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ABSTRACT :

We review briefly the various observations showing the unresolved nature of the small-scale solar magnetic fields. The horizontal scale-length of these magnetic elements is only a fraction of one arc second (< 0"2). The observed average field strength is weak (from 20 gauss up to a few hundred gauss) and the true field strength should be higher. But the high value (> 1500 gauss) inferred by the observers is model-dependent. The magnetic models of atmosphere they used contain many crude assumptions : the neglect of the vertical variations of the physical parameters with height, the "dynamically thin tube" assumption, the neglect of velocities, even subsonic, etc...

We propose a self-consistent hydromagnetic model of magnetic flux tubes. The observed downdraft provides a mechanism for the facular heating by transporting an excess of entropy (the excess is between the magnetic tube and outside) from the chromospheric layers down to the photosphere. Two different Bernoulli solutions are studied :

- the critical solution C_1 exhibits a temperature excess of 1000°K localized in the upper photosphere and a downdraft decelerating with increasing depth. The magnetic field strength at the base of the photosphere is low (300 gauss, for an "optically thin" tube (model 1) up to 800 gauss if we allow an empirical departure from the "optically thin" assumption (model 2)). This solution seems to be more appropriate to the upper levels of the photosphere or to the chromosphere .

- the other family of solutions predicts an excess of temperature which can explain the center-to-limb effect of the continuum facula. The magnetic field strength at the base of the photosphere does not exceed 1300 gauss. The flow is adiabatic, accelerating rapidly inwards. The theoretical velocity of 7 km s^{-1} obtained at the base of the photosphere can be substantially reduced if the bright facula has the dimensions of filigrees.

We suggest that a realistic picture of the small-scale magnetic fields will be obtained by the particular Bernoulli solution which behaves thermodynamically as the critical solution in the upper layers and becomes adiabatic in the lower layers.

INTRODUCTION

For the last decade, many attempts have been made to understand the physics of the small-scale solar magnetic fields. The magnetic elements beeing unresolved with the present telescopes, the interpretation of the averaged quantities observed requires the elaboration of magnetic models. Hydrostatic solutions (with radiative equilibrium) have been extensively used and lead to a strong field strength (> 1500 gauss) at the base of the photosphere. However, the presence of a flow, even subsonic, has a considerable importance : it carries the thermal energy which controls the temperature and the temperature affects back the dynamics. This coupling will modify deeply the magnetic structure. Consequently, the hydrodynamical situation is very different from the hydrostatic one. Since the interpretation of unresolved observations is not unique, we cannot exclude the possibility for the two types of solution to exist in the unresolved fine structures.

In this paper, we first review some observations showing that the small-scale fields are unresolved (part A). Then, we point out the difficulties to interpret the "averaged" observations with the help of too simple assumptions (part B). Finally, we propose a new heating mechanism for the magnetic tubes with various thermodynamical conditions for the fluid (part C). This mechanism is valid throughout the solar atmosphere, but in the present stage, the results are rather qualitative and should be considered as a step towards a better understanding of the solar network.

A) OBSERVATIONAL EVIDENCE FOR THE UNRESOLVED NATURE OF THE SMALL-SCALE FIELDS.

Simultaneous observations of several photospheric lines with a magnetograph (Harvey and Livingston (1969) ; Frazier and Stenflo (1972, 1978) ; Wiehr (1978) ; Semel (1980 b)) showed a very significant incoherence in the measured magnetic field, both in faculae and network. The ratios of the magnetograph signals for two given lines were also found to be constant and independent of the observed field strength. At first, Harvey and Livingston attributed this incoherence to a line weakening caused by an excess of temperature. For a weak field, the magnetograph signal is proportional to the slope of the line profile. If this slope is sensitive to the temperature, then the magnetograph signal is sensitive to the temperature as well.

However, these authors observed a broadening in the faculae larger than in the quiet photosphere, for the 5250.2 Å line of Iron I. They interpreted the broadening as a manifestation of a magnetic turbulence corresponding to about 500 gauss.

It is known that the magnetograph saturation e.g., the non linear response of the magnetograph for strong Zeeman displacements could explain partly the incoherence of the magnetograph measurements. By measuring two lines with different Landé factor (g), hence with different magnetograph saturation, a one kilogauss field was necessary to explain the ratio of the magnetograph signal for these 2 lines. By assuming a large scale distribution of magnetic field, Stenflo deduced the amplitude of the peak of 2 kilogauss. The constancy of the magnetograph signals' ratios for the two lines and the non-dependence with the field strength was an argument in favor of a "unique" magnetic structure (Frazier and Stenflo, 1972).

Similar observations have been carried out by Frazier (1974) and Wiehr (1978) with three lines. Wiehr found the magnetic structure was not unique and the field strength could range from 1200 gauss to 2500 gauss, both in active regions and in the network.

Harvey and Hall (1975) observed an infra-red line at 1,5 μ. This choice of the wavelength is particularly advantageous because the Zeeman displacement (proportional to λ^2) is much larger than the Döppler broadening (proportional to λ). The observed profiles of the circular polarization, that is the Stokes parameter V, shows peaks corresponding to a field strength of 1500 gauss and a Döppler shift yielding 1.6 Km s^{-1}.

Other types of observations are also suggesting that the magnetic field could be concentrated and probably strong.

The filigrees observed by Dunn and Zirker (1973) have dimensions much inferior to 1 arc second. If the magnetic field is concentrated in the filigrees, it should be very strong.

The line gaps observed by Sheeley (1967) with a very good seeing might be explained by a Zeeman weakening, as well. Wilson (1971), Rees (1973), Chapman (1977) elaborated facular models from these data. In general, no model could fit with all observed line weakenings. The field strength proposed by Chapman is about 1800 gauss at $\tau_{5000} = 1$ in the magnetic tube. His model does not fit with strong lines and non L.T.E. effects are invoked to be the main reason.

Simon and Zirker (1974) obtained spectra with excellent spatial resolution. They looked for the smallest magnetic structure to fit with the filigrees. They found that the magnetic field covers an area much larger than the filigrees'. For many cases, the magnetic intensity was weak. If Stenflo's conjecture is correct, namely the field distribution is the same for all structures and strong, the magnetic elements observed by Simon and Zirker consist of clumps of flux tubes.

Another confirmation of the unresolved nature of the magnetic field was obtained by Semel (1980 b) using 12 lines recorded simultaneously (1980 a). The incoherence between the magnetic field intensities deduced from each of these lines proves that the magnetic field is unresolved, and the line weakening is spatially correlated with the magnetic field.

In conclusion, *the magnetic structure is obviously unresolved.* The horizontal scale length is inferior to the best resolving power of the present observations, only a fraction of one arc second. *The strength of the magnetic field is certainly much higher than what we observe.* The estimations are : 1800 gauss (Chapman), 2000 gauss (Frazier and Stenflo), 1600 gauss (Harvey), > 1500 gauss (Wiehr). Besides, it is very likely that a *downdraft accelerating with increasing depth exists in the magnetic tube* (Giovanelli and Slaughter, 1977).

B) CRITICAL REVIEW OF THE INTERPRETATIONS OF OBSERVATIONS.

We should keep in mind that the observed magnetic field is usually small, at least one order of magnitude less than what the strong values generally claimed. *The reduction of the data is more or less model dependent. The assumption of a "thin" magnetic tube is always used.* In particular, the curvature of the lines of force is neglected and the Laplace forces are reduced to the magnetic pressure only, as follows :

$$(P_{gaz} + B^2/8\pi)_{in} = (P_{gaz})_{out} \qquad (1)$$

this sets a constraint on the maximum field strength and its variation with height. Although the line formation calculations are considerably easier with such an assumption, we may question its validity. A priori, we would expect that the lateral dimension of a thin tube is much smaller than the vertical scale height variations. Assuming a tube of 260 km diameter, the magnetic pressure scale height is half the diameter and is the same as the external gaz pressure scale height (130 km). So, *we cannot neglect the variation of both geometry and physical quantities with height.* Moreover, in the frozen field assumption, the presence of a downdraft increasing with increasing depth will make the variation of the magnetic scale height even more rapid, for continuity reasons (B is proportional to ρu). The magnetic field scale height will be much smaller than in the hydrostatic case. Then, the interpretations of observations become questionable if the variations of the physical parameters with height are not taken into account.

For example, Frazier and Stenflo (1978) measured the brightness, the velocity and the polarization in two lines simultaneously. While the polarization was in favor of a strong field, velocity and brightness were in favor of a weak field. There was no way to explain all the obervables. It is very likely that the difficulties in interpreting their data come from the neglect of height variations and the assumption of a too simple distribution of the physical parameters. A more sophisticated model including height variation is necessary.

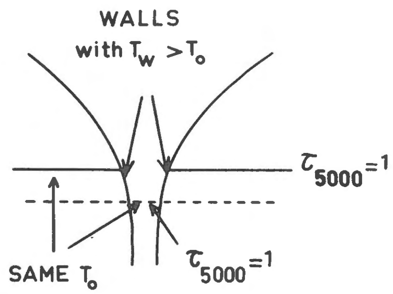
Wiehr (1979) made an experiment to find out what is the limit flux coming out of a bright facular point. Observing the 5250.2 Å line with an aperture of 4" by 4", the measured field was found to be either higher than 20 gauss or within the noise. If there is a limit flux, the magnetograph signal should be inversely proportional to the magnetograph aperture. In fact, Wiehr found an increase of the magnetograph signal when decreasing the aperture, but not in the expected ratio. The concept of limit flux in a concentrated magnetic field is, therefore, questionable.

Chapman's model (1977) includes a height variation of the magnetic field, but he has neglected the observed velocities. He assumes several empirical models to explain the excess of temperature observed in facular regions. He considers different field intensities and the percentage of the area occupied by the magnetic tubes. He found that the best solution is obtained for his model 7 B 13, giving a temperature excess of 1000°K, a magnetic field strength of 1800 gauss at $\tau_{5000,\ facula} = 1$. This depth is 165 km below the level $\tau_{5000} = 1$ in the H.S.R.A. reference atmosphere. However, not all the lines he observed could fit the model adopted;out of 10 lines, 4 gave a too strong or a too weak field and were rejected on the grounds that these strong lines were influenced by non L.T.E. effects. We think that Chapman's approach may give good temperature models but is not adequate to determine the magnetic field strength.

To illustrate this, let's consider the two lines 5250.2 Å and 5247.1 Å belonging to the same multiplet of Iron I. The profiles of the two lines are practically identical in the quiet photosphere. In faculae, they are substantially weakened but the difference in their profiles is still very small, in spite of quite different Landé factors (see Fig. 7 a of Chapman (1977)). So, the temperature excess is the main cause of the line weakening and the contribution of the Zeeman effect is small. Therefore, all the uncertainties involved in the model calculated by Chapman (abundance, oscillator strength, microturbulence, temperature excess etc...) will affect heavily the small difference between the two weakened lines. As a result, the determination of the magnetic field is difficult.

Spruit (1976) studies a magnetostatic solution of axially symetric flux tubes and calculates the energy balance of these tubes. The interior pressure is lower than the outside pressure, according to equation (1). He explains the excess of brightness in the continuum faculae by the fact that one is seeing the walls of the tube, for an heliographic angle $\theta > 0$ (see Fig. 1).

Fig. 1 : MODEL OF
MAGNETOSTATIC FLUX TUBE
(SPRUIT, 1976)



We can summarize some of our objections to the present picture :

1) The actual resolution of the telescopes cannot isolate the walls of Spruit's model. On the other hand, the observations indicate an excess of flux coming out from facular regions. Spruit assumes that the excess of flux observed in the magnetic tube has been radiated laterally through the walls from the surrounding regions. But his assumption does not seem to be supported by the observations (the bright facula does not appear to be surrounded by a dark ring). The origin of the excess of flux and the flux conservation are fundamental problems which should be carefully studied.

2) Can we really assume so much brightness excess from the walls ? Spruit assumes that the walls have no thickness and the effective temperature for the outflow radiation from the wall is the same outside the wall. In reality, the walls have a finite thickness and the energy transfer through it will give a temperature gradient and a reduced temperature for the wall.

3) He estimates the energy transport through the walls by using the approximation of the diffusion equation. This approximation is valid for an optically thin tube.

Below $\tau = 1$, the tube is thick, therefore the source function is overestimated.

In short, the radiative transfer through the walls requires a much more complicated treatment than the approach made by Spruit. It is very likely that a more rigourous treatment of the radiative transfer, even one-dimensional, would fail to fit with the observations of the continuum faculae. In any case, Spruit's mechanism is restricted to the low photosphere and does not explain the heating of the chromospheric faculae.

C) HYDROMAGNETIC APPROACH FOR THE SOLAR SMALL-SCALE FIELDS.

There are observational and theoritical motivations to look for a magnetohydrodynamic solution of the solar magnetic flux tubes.

1) The stability analysis of a thin magnetic tube in hydrostatic equilibrium indicate that the magnetic field necessary for stabilizing the tube should exceed 1800 gauss at $\tau_{5000} = 1$ (Unno and Ando, 1979), which means an almost empty tube. *Below this value, the tube is convectively unstable and a flow will set in.* From thermodynamical considerations, a downdraft is more plausible (Ribes and Unno, 1976).

2) *The observations indicate the presence of velocities in the magnetic tube* (Frazier, 1970 ; Harvey and Hall, 1975 ; Giovanelli and Slaughter, 1977 ; Frazier and Stenflo, 1978). The downdraft is accelerating with increasing depth, showing a rapid increase in the inner photosphere.

3) *Solutions with non-zero velocities are quite different from those with zero velocities* (Unno, 1980).

On one hand, the necessity of keeping the mass flux constant makes the hydrostatic models highly inconsistent with velocities, even small. Giovanelli (1977) suggests that the matter can move across the lines of force near the temperature minimum and below. Therefore, the relation $B \alpha \rho u$ needs not to be satisfied. Hovewer, the process requires the cross-section of the tube to be small. In the upper photosphere, the lines of force have already spread out and the inflow of matter will be restricted to the skin of the magnetic tube. So, in our model, we still keep the field "frozen" and we let the magnetic configuration open fast enough to satisfy the mass conservation.

On the other hand, the presence of velocities affect considerably the energy balance through the transport of entropy. In the hydrostatic case, the balance is between emission and absorption of radiation. In the hydrodynamical case, the term of entropy should be added. An enhanced emission is necessary to compensate the entropy excess transported by the downdraft. The resulting temperature excess is significant in the upper layers where opacity and density are low.

To illustrate this basic difference, we discuss now a hydromagnetic model of solar faculae (Unno and Ribes, 1979). We consider a "thin" magnetic tube embedded in the photosphere. The basic equations governing the flow in the tube are given by :

$$P + B^2/8\pi = P_R \tag{1}$$

$$\rho\ u\ \sigma = C_1 \tag{2}$$

$$B\ \sigma = C_2 \tag{3}$$

$$\frac{d}{dZ}\left(\frac{u^2}{2}\right) + \frac{1}{\rho}\frac{dP}{dZ} + g = 0 \tag{4}$$

$$T\ u\ dS/dZ = \frac{1}{\rho}\nabla.F = 4\ \pi(K_P\ B - K_J\ J) \tag{5}$$

where ρ, T, S, u, σ, B, J, F, K_P, K_J, C_1, C_2 and g denote the density, the temperature, the specific entropy, the downdraft speed, the cross section of the tube, the integrated source function (black body), the integrated mean intensity, the radiative flux, the Planck-mean absorption coefficient, the mean absorption coefficient weighted by the specific mean intensity, the mass flux, the magnetic flux and the gravity respectively. The flow is driven by the difference between the gravity and the pressure gradient.

The equations are coupled and a general solution is difficult to obtain. So, we proceed as follows :

1) First, we assume an entropy (or a temperature) distribution (Fig. 2) as a solution of the energy equation (5) and we solve the Bernoulli flow (that is, the flow along the lines of force, equations 1 to 4) for the density, the pressure and the velocity as a function of height.

2) Then, we check the consistency of the energy equation. The best fit is obtained by adjusting the free parameters of the analytical function which describes the entropy distribution.

the general Bernoulli flow is characterized by two critical solutions C_1 and C_2

passing through the singular point, and four families of solutions (a, b, d, e) (Fig. 3). We have eliminated the critical solution C_2 and the families b and e which are restricted to the deep layers where our assumption of a thin tube, without viscosity etc. are not valid. The family a does not connect sufficiently distant layers and has been disregarded too.

The critical solution C_1 exhibits the following properties (see Fig. 4) : *the flow speed is large,* although *subsonic*, at the top of the photosphere and *decelerates rapidly with increasing depth.* This is in contradiction with Giovanelli and Slaughter's observations (1977) of a downdraft accelerating inwards. *A temperature excess of 1000°K is localized in the upper photosphere*, in agreement with the line weakenings. But there is a significant difference for the continuum center-to-limb variation as observed by Müller (1975). *The magnetic field strength is low* : at $\tau_{5000} = 1$, *300 gauss for an optically thin tube* (model 1), *up to 800 gauss if we allow a departure from the opticelly thin assumption* (model 2) (the departure is parametrized by a dilution factor which varies empirically from 1 (at $\tau = 1$) up to 1.5 at $\tau = 0.01$). The corresponding magnetic scale heights are 340 km and 500 km respectively.

These models (1) and (2) describe a new self-consistent heating mechanism necessary to explain the brightness enhancement of faculae, in the lines as well as in the continuum. It is the competition between the excess of entropy transported by the downdraft and the radiation loss. The two models presented above underline the role of the dilution factor. However, the infinitesimally thin tube model (n° 1) seems to fit more with the characteristics of the chromospheric faculae and do not explain the main properties of the photospheric faculae. In particular, a relevant solution should approach the upper branch of the critical solution C_1 and differ from it in the lower levels. Among the d-type solutions, there is one which seems to fulfill the requirement (see d_{Fac} in Fig. 3). Since the thermodynamics in the lower photosphere is unknown, we approximate it by a polytropic law, as follows :

$$P = k\,\rho^{\Gamma} \qquad (7)$$

where Γ is the polytropic index. Moreover, we decide to put more weight on the recent photospheric observations, namely, the distribution of velocity reported by Giovanelli and Slaughter (1977), the continuum center-to-limb variation (Müller, 1975 ; Hirayama, 1978) and a strong field.

The Bernoulli flow is reduced to two equations :

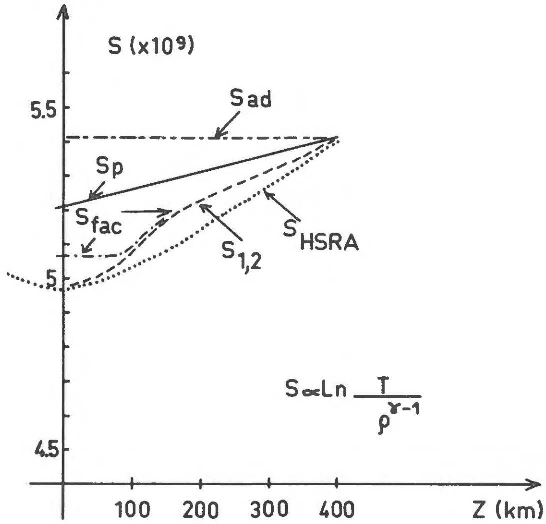


Fig. 2 : represents various possible thermodynamical behaviours of the fluid in a magnetic tube.

A realistic entropy distribution for the facula (S_{FAC}) is probably the combination of the chain line (adiabatic flow) with the dashed line (Models 1 and 2).

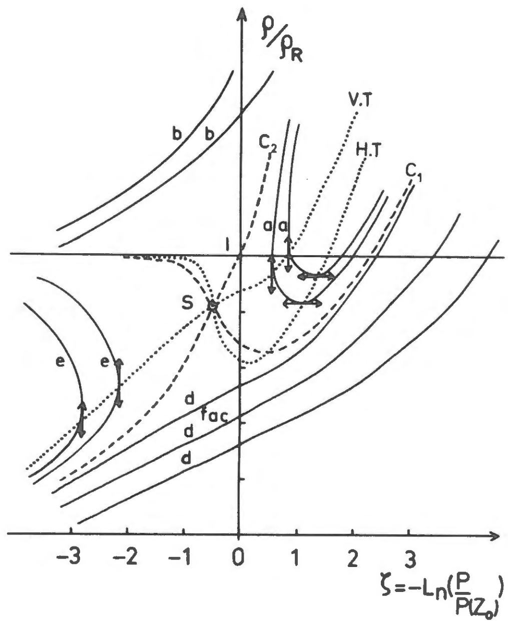


Fig. 3 : shows the different Bernoulli solutions for a given entropy. Note that there is a particular d-type solution (d_{fac}) which approaches the critical solution C_1 in the upper layers and diverge from it in the low photosphere.

$$\frac{u^2}{2} \rho^2 [P_R - P]^{-1} = \text{Constante} \quad (8)$$

$$\frac{u^2}{2} + \Gamma (\Gamma - 1)^{-1} \frac{R}{\mu} T + gZ = \text{Constante} \quad (9)$$

By inspection of equation 8, $\rho^2 u^2$ should increase rapidly inwards to allow a strong magnetic pressure on the other hand, the equation of motion (9) shows that a large variation of the gravitational potential gZ should be balanced either by a rapid increase of u^2 or by the second term representing a kind of potential energy. The T(Z) relation from Müller requires Γ to be close to unity, but the gaz pressure decreases too rapidly inwards with a resulting low magnetic field. So, a strong field requires Γ to be close to the adiabatic value. The characteristics of the d-type adiabatic steady flow are illustrated in Fig. 4 : *the magnetic field strength is about 1300 gauss* at $\tau_{5000} = 1$ and diverges rapidly, with a scale height of 110 km. The *flow is nearly adiabatic* and *accelerates downward up to 7 km s^{-1}*. This value is 4 times larger than the velocity observed by Harvey and Hall (1975). However, if the bright faculae have the dimensions of the filigrees (200 km or less), the temperature excess at $\tau_{5000} = 1$ is still important (Koutchmy, 1977). A temperature excess of 1700°K at this depth would reduce the theoritical flow speed down to 2 km s^{-1}. *Our parameter fitting is approximate because the interpretations of observations are uncertain.* Nevertheless, we can understand, at least qualitatively, the heating of faculae by the thermodynamical behaviour of the fluid.

CONCLUSION

The observations have shown that the magnetic field in the faculae and in the network is unresolved, with a lateral dimension of 200 km or less.

The vertical scale height variations are even smaller and cannot be neglected.

A downdraft is observed and provides a consistent mechanism for the facular heating by transporting the entropy excess from the chromospheric layers. A three dimensional radiative transfer is necessary to proceed in our investigations. The energy balance should also include the wave generation and dissipation. The stability of steady flows is another problem worth investigating.

Where and why the magnetic field is concentrated is a very intriguing problem which is not considered here. But very likely, the concentration is conditioned by the convection zone, and the observable layers play a rather passive role in this context.

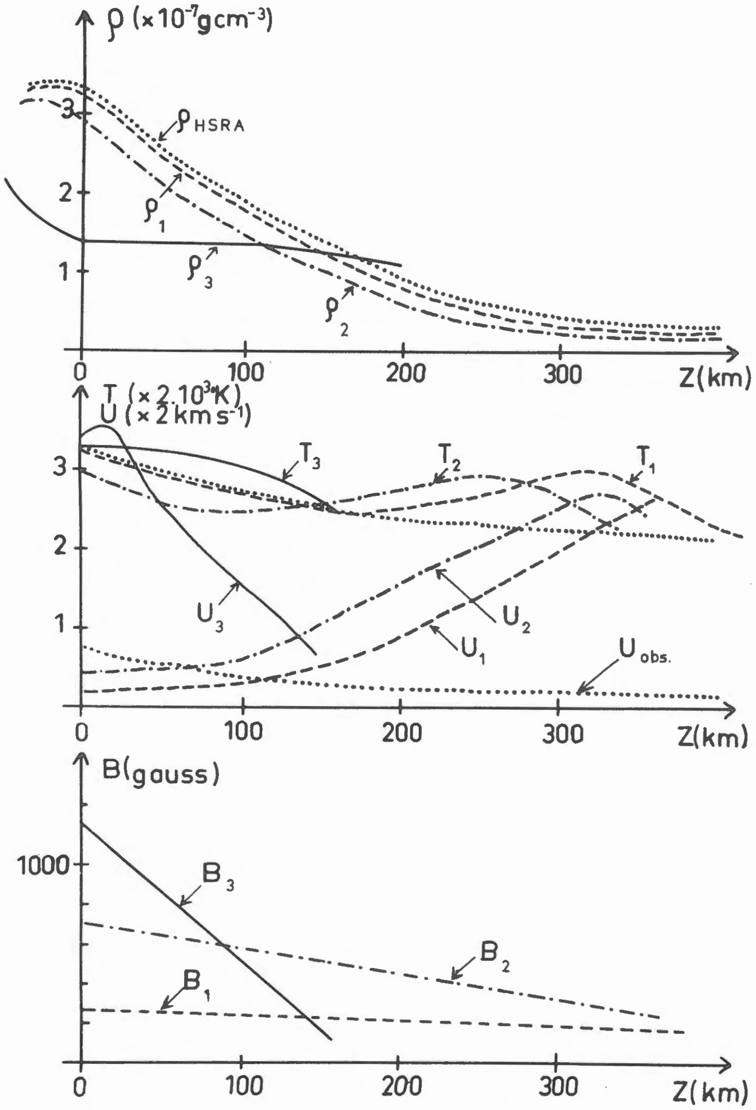


Fig. 4 : summarizes the variations of the physical parameters (S, T, u and B) with height, for the various hydromagnetic models refered by the indices 1, 2 and 3. Also, is represented the H.S.R.A. model, for comparison.

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