THE LOWER SOLAR ATMOSPHERE

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Abstract. This "rapporteur" report discusses the solar photosphere and low chromosphere in the context of chemical composition studies. The highly dynamical nature of the photosphere does not seem to jeopardize precise determination of solar abundances in classical fashion. It is still an open question how the highly dynamical nature of the low chromosphere contributes to first ionization potential (FIP) fractionation.

Key words: Solar composition, solar atmosphere

1. Lower Atmosphere: Context

This is a "consumer" report on the lower solar atmosphere (photosphere and low chromosphere, the latter defined as the regime where hydrogen is not yet fully ionized) in its role as a provider of diagnostics for solar composition studies. The topic is reviewed by Solanki (1998), Judge and Peter (1998) and Grevesse and Sauval (1998) elsewhere in this volume.

Let me begin by placing the lower atmosphere into its context. This meeting is unusual by combining research and researchers from the innermost to the outermost solar reaches — a wide variety sketched broadly in Figure 1.

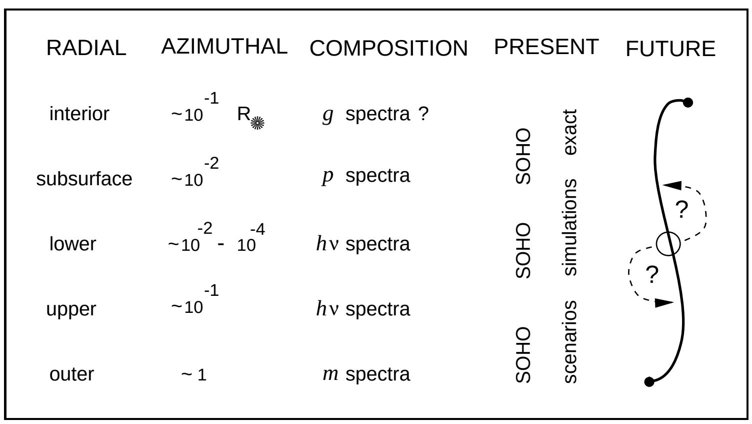

Figure 1. Very broad overview of solar composition studies.

The first column labeled "radial" describes the overall structure of the workshop. It splits the sun and heliosphere into different radial domains that also characterize the splitting of solar physicists into separate estates. The lower atmosphere can be seen as the pivot. Inwardly, it provides the surface diagnostics (Doppler shifts, irradiance variations, magnetic field patterns) for the subsurface studies on how our star is made. Outwardly, it provides the boundary conditions (mechanical energy production, field structure, field pattern evolution) that make the solar atmosphere such an exciting laboratory to MHD and plasma physicists. Of course, it also provides the light that we see and that maintains our ecosphere, but the production of photospheric radiation is basic course material* rather than food for ISSI workshops these days.

The second column gives rough estimates of the lateral fine-structure scale that is typically discussed for each regime. The lower atmosphere stands out by being most detailed, down to the $\Delta r = 10^{-4}\,R_\odot = 0.1''$ holy grail of optical solar telescopes, sometimes nearly glimpsed by the SVST** and DOT*** telescopes on La Palma when the seeing is superb, but generally awaiting the development of image restoration techniques, in particular adaptive optics, and/or larger telescope apertures in space than that of SOHO's MDI/SOI‡ and TRACE‡‡. The plethora of detail on the solar surface tends to make non-solar astrophysicists unhappy, but it does harbor rich diagnostics of astrophysical structures and processes at the intrinsic scales at which the actual physics operates – unresolvable outside the solar system. The problem is that the dynamical nature and juxtapositon of the atmospheric structures and processes, especially those having to do with the complexities of magnetism, require comprehensive diagnostics combining high angular, temporal, spectral and polarimetric resolution over large fields, long times and many wavelengths (heights) simultaneously — Judge and Peter (1998) typecast the chromosphere as the most difficult solar regime.

The third column indicates the diagnostics used to study solar composition. The sub-surface p stands for the pressure eigenmodes, with gravity modes (g) yet a SOHO tantalizer. The outer m stands for the mass, charge, and energy of particles, collected rather far away from the solar surface, within the heliosphere. In between, composition studies rely on photon spectra. The solar-atmosphere composition is directly portrayed by the line strengths in the optically thin conditions of the upper atmosphere, while they affect only the source function sampling location in the optically thick conditions deeper down. Nevertheless, thick line formation is much easier to model than thin line formation (Solanki, 1998), so that the photospheric abundances are the ones we know precisely (Grevesse and Sauval, 1998).

The column labeled "present" is an easy one! SOHO was heralded as an inside-out solar-interior-to-outer-heliosphere mission, and that is precisely what it has turned out to be. On the observational side, this whole-sun meeting is dominated by SOHO research, an obvious tribute to SOHO's success. On the interpretational side, there is an interesting gradient in which mathematical exactness in p-mode

* lecture notes at `http://www.astro.uu.nl/~rutten`
** `http://www.astro.su.se/groups/solar/solar.html`
*** `http://www.astro.uu.nl/~rutten/dot`
‡ `http://soi.stanford.edu`
‡‡ `http://www.space.lockheed.com/TRACE`

fitting gives way to the occasional realism reached by numerical hydrodynamical and MHD simulations of surface-layer structuring, and to the yet exploratory nature of the scenarios in vogue further out. For the lower atmosphere, numerical simulations contribute the largest advances at present. While the optical telescopes are (too) slowly approaching their $0.1''$ grail, spectacular progress is made numerically, in particular in the convection simulations of Nordlund and Stein (1990), the acoustic shock simulations of Carlsson and Stein (1997) and the fluxtube simulations of Steiner *et al.* (1998).

The final column labeled "future" is less easy. It seems likely that the domains must and will come together, in holism that exceeds just multi-diagnostic observing by integrating interior, atmospheric, and outer solar structure to a larger extent than the congregation assembled here is wont to (want). Such integral synthesis seems yet far off, but as a starter I suggest a low-chromosphere connection to both subsurface and outer-atmosphere phenomena below (dotted arrows).

2. Lower Atmosphere: Radial Scene

Figure 2 is a cartoon summarizing the radial stratification of the lower atmosphere. It also summarizes points discussed in the reviews of Grevesse and Sauval (1998), Solanki (1998) and Judge and Peter (1998) in this volume. It sketches "standard models of the solar atmosphere" where the term "model" implies just a temperature-depth relation because generally, hydrostatic equilibrium is assumed to derive the corresponding density stratification. The difference with stellar model atmospheres is that the latter tend to be based on the assumption of flux-constancy (radiative equilibrium above the convective regime), whereas solar models tend to be empirical in some respect.

This diagram portrays the sun as seen by spectroscopists who determine solar abundances in classical fashion (and then, rather boldly, call them "cosmic", *e.g.*, Allen, 1976). The most classic model portrayed here is the one by Holweger (1967), which is usually quoted as its slightly-modified HOLMUL reincarnation by Holweger and Müller (1974). Holweger inverted the observed line-core brightness temperatures of optical lines at disk center, especially Fe I lines, into a best-fitting $T(\tau)$ relation assuming LTE line formation (i. e., line formation under local thermodynamic equilibrium conditions). In simple Eddington-Barbier terms with $I(\mu) \approx B(T[\tau = \mu])$, each disk-center line core displays the temperature where it reaches total optical depth unity; by plotting these temperatures against known gf-value ratios for members of multiplets, Holweger obtained segments of a $T(\tau)$ model that he shifted together and combined with various continuous opacity sources and hydrostatic equilibrium to obtain monotonic $T(\tau)$ and $\tau(h)$ stratifications. Holweger's model has no chromospheric temperature rise because the optical Fe I lines do not possess self-reversed emission cores (the only optical lines that do so are Ca II H & K, a separate story).

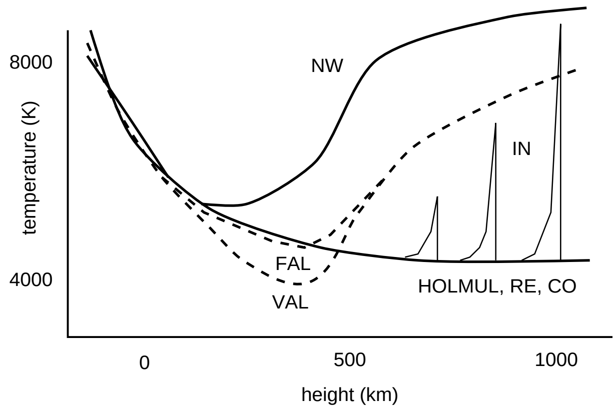

Figure 2. Cartoon of the radial stratification of the lower solar atmosphere outside active regions. See also Fig. 1 of Solanki's (1998) review and Fig. 1 of Judge and Peter's (1998) review. The sketched models VAL, FAL, HOLMUL and RE (radiative equilibrium) are all "classical" in describing static plane-parallel stratifications that obey hydrostatic equilibrium. Convective energy transport affects the deepest layers and produces slightly different stratifications in and between granules. The middle photosphere (i. e. around 200 km height) is closest to the classical plane-layer-plus-turbulence paradigm. The temperature minimum region around h = 400 km does not exist anymore; the apparent VAL–FAL chromospheric temperature rise in the non-magnetic internetwork regime (IN) is now thought to represent intermittent shocks in an otherwise cool atmosphere (Carlsson and Stein, 1995). The shocks do not heat or lift the time-averaged atmosphere which remains cool out to $h > 1000$ km and explains the deep cores of the infrared CO lines. In magnetic network structures (NW) the temperature rise occurs much deeper (see Fig. 6 of Solanki's 1998 review), but we don't know where or how or why. VAL stands for the continua-fitting model by Vernazza *et al.* (1981), FAL for its update by Fontenla *et al.* (1993), HOLMUL for the update by Holweger and Müller (1974) of the line-fitting model of Holweger (1967), RE for radiative-equilibrium models such as the one by Bell *et al.* (1976). CO designates yet underived time-averaged models based on the infrared CO line cores (cf. Avrett, 1995).

Chromospheric temperature rises are a fixture of the major other class of empirical models, those inverting the observed disk-center continua Eddington-Barbier-wise into temperature stratifications. The technique is essentially the same as Holweger's; the difference is that the required variation in height sampling now comes from the variation of continuous opacity over the whole spectrum, with the chromosphere sampled by the ultraviolet shortward of 160 nm and the infrared longward of 160 μm. In the infrared LTE is a good assumption, but it fails in the ultraviolet where the bound-free ionization edges behave much like resonant scattering lines so that their source functions follow the angle-averaged intensity J_ν more closely than the Planck function B_ν. The inversion therefore has to take $J_\nu \neq B_\nu$ departures into account. This was done with impressive sophistication by Avrett and coworkers in Vernazza, Avrett and Loeser (1973, 1976, 1981 = VAL), Avrett (1985), Maltby *et al.* (1986) and Fontenla, Avrett and Loeser (1993 = FAL).

The main differences between VAL and HOLMUL are the VAL chromospheric temperature rise above h = 400 km and the lower VAL temperature just below this height. The latter produces appreciable $J_\nu > B_\nu$ excess in the violet and ultraviolet continua. It causes large NLTE (i. e. non-LTE) ionization departures for minority ionization stages such as Fe I (Lites, 1972). I have shown that one may actually derive the HOLMUL model from the VAL model by admitting Fe I NLTE departures in Holweger's LTE inversion procedure (Rutten and Kostik, 1982; cf. Rutten 1988, 1990). At the time, I felt that this disproved Holweger's sarcasm that "NLTE departures tend to arise in the computer when the modeling is incomplete" — I thought that his model arose erroneously from his own computer because he ignored departures from LTE. However, the deep dip of VAL went away when Avrett included more and more lines from Kurucz's gigantic atomic tabulations in his computer. The ultraviolet line haze diminishes J_ν and so brought the FAL photosphere close to HOLMUL while doing away with Fe I NLTE effects, adhering to Holweger's claim.

More recently, a similar change from FAL back to HOLMUL has affected the chromosphere. The successful numerical reproduction by Carlsson and Stein (1997) of the so-called Ca II H_{2V} grains observed by Lites *et al.* (1993) has led Carlsson and Stein (1995) to propose that the non-magnetic parts of the low chromosphere are actually cool, but that acoustic shocks that pass through intermittently are sufficiently bright in the ultraviolet that the time-averaged ultraviolet spectrum requires an apparent temperature rise when inverted in Avrett's continua-fitting procedure. The shocks are weak and seem not to lift or heat the chromosphere persistently, but produce enough temperature variation along the line of sight that the nonlinear $\partial B_\nu / \partial T$ response in the ultraviolet makes the average chromosphere appear hot even though it remains cool (cf. review by Judge and Peter, 1998). This change of view, from an ubiquitous temperature rise above h = 400 km to an extended cool, yet shock-ridden atmosphere must also explain the long-standing CO line-formation problem raised by Ayres (*e.g.*, Ayres, 1981; Ayres *et al.*, 1986; Ayres and Rabin, 1996). The final CO paper hasn't yet been written, but it is quite likely that the infrared CO lines display the cool time-averaged structure without much sensitivity to the temporary disruptions that are observed in Ca II H & K and that dominate the ultraviolet continuum emission. Similarly, the shocked-but-cool clapotispheric picture may explain various infrared, sub-mm and mm observations that indicate cool extent larger than VAL-predicted (*e.g.*, Labrum *et al.*, 1978; Horne *et al.*, 1981; Wannier *et al.*, 1983; Lindsey *et al.*, 1986; Roellig *et al.*, 1991; Deming *et al.*, 1992; Belkora *et al.*, 1992; Ewell *et al.*, 1993; White and Kundu, 1994; Solanki *et al.*, 1994).

The RE in Fig. 2 stands for stellar-like theoretical radiative-equilibrium models (cf. Gustafsson and Jorgensen, 1994). The fact that they follow HOLMUL closely suggests that the solar photosphere obeys radiative equilibrium closely. The differences are largest in the deepest layers where the theoretical model takes convective energy transport into account.

3. Lower Atmosphere: Azimuthal Scene

Figure 3 again portrays the lower atmosphere cartoon-wise, but now viewed from the side and emphasizing its inhomogeneities — just as in Fig. 2 of the review by Judge and Peter (1998). Even outside active regions (spots and plage, not illustrated here), the magnetic field is a major agent. New flux that emerges from below tends to quickly assume evacuated kilogauss fluxtube format and to congregate in the loosely defined network pattern (Hagenaar *et al.*, 1997). The latter may be mapped with magnetographs (magnetic network), imaged in the Ca II H & K lines and in many ultraviolet lines (chromospheric network), is outlined by tiny "bright points" in the very best images taken in the Fraunhofer G-band around 430.5 nm, and outlines the cell borders of the supergranulation, although incompletely. The fast congregation results in the strong dichotomy between kilogauss-rich network and kilogauss-poor internetwork (the non-network areas).

The network fluxtubes are modelled in most detail in the Freiburg time-dependent 2D simulations of Steiner *et al.* (1998). They expand with height, magnetostatically in the "Zürich wine glass model" by Solanki and coworkers (*e.g.*, Solanki and Steiner, 1990; Solanki *et al.*, 1991; Bündte *et al.*, 1993; Bruls and Solanki, 1995; Briand and Solanki, 1995) and dynamically in the Freiburg simulations. Depending on polarity and tube separations, the resulting canopies above which magnetic field pervades the entire medium should be located lower or higher in the chromosphere, or possess an open-out structure as sketched in Fig. 2 of Judge and Peter (1998).

Internetwork fields are even more elusive than overlying canopies (*e.g.*, Zwaan, 1987). Initially described by Livingston and Harvey (1971) as ubiquitous bipolar patterns of random nature, in which the single-polarity patches extend over 2–10 arcsec, their properties and nature remain controversial. Keller *et al.* (1994) derived a sub-kiloGauss upper limit to the intrinsic field strength B while $B \approx$ 500 Gauss was reported by Lin (1995; cf. also Solanki *et al.*, 1996). Internetwork features with this strength make up a relatively rare class, however (Wang *et al.*, 1995; Wang *et al.*, 1996; Lee *et al.*, 1997; Meunier *et al.*, 1998). The more general, weaker "salt-and-pepper" background is perhaps best displayed in the lowest-flux parts of Fig. 4 of Lites *et al.* (1996), who found an additional class of short-lived, compact internetwork features with predominantly horizontal field orientation (HIF's). Finally, a truly weak background field may exist as well (Faurobert-Scholl, 1993; Bianda *et al.*, 1998 — but see Landi Degl'Innocenti, 1998).

The dynamical phenomena are strongly affected by the presence of magnetic fields. Even the granulation gets "abnormal", i. e. inhibited when there are too many fluxtubes as in a plage (Title *et al.*, 1992; Berger *et al.*, 1998). The chromospheric dynamics higher up is markedly different in the network and internetwork domains (Lites *et al.*, 1993). The so-called three-minute oscillation dominates in the internetwork areas. It consists of a wide-band acoustical wave spectrum of which the higher frequencies have more upward propagation; shock steepening, shock overtaking and shock colaescence occur in the layers around h = 800 – 1000 km, where

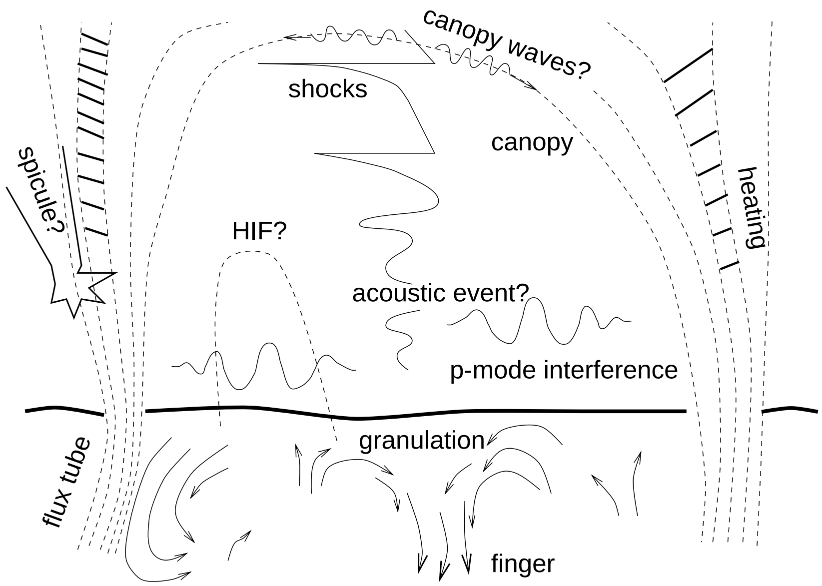

Figure 3. Cartoon of the structure of the lower solar atmosphere outside active regions. See also Fig. 2 of the review by Judge and Peter (1998). It shows, schematically, various phenomena in a vertical cut through the lower atmosphere, and covers about the same radial domain as portrayed in Fig. 2. The magnetic network (dashed fieldlines) is thought to be made up of thin 1400 Gauss fluxtubes that are best seen in the 430.5 nm G band (Title and Berger, 1996; magnificent Scharmer-Berger poster available at `http://diapason.lmsal.com/∼berger/`). They tend to be embedded in fast downflows that occasionally cause upward propagating shocks (Steiner *et al.*, 1998) that seem most likely to cause the overly ignored spicules (Beckers, 1968). Higher up, the field is expected to expand and form a low-lying magnetic canopy when it connects with neighboring network field (*e.g.,* Giovanelli and Jones, 1982; Jones and Giovanelli, 1983; Solanki and Steiner, 1990; Bruls and Solanki, 1995; Briand and Solanki, 1995). The magnetic heating, whatever way it is done, does apparently not expand with the field since the network remains sharply grained in ultraviolet images diagnosing much higher temperatures than sketched here. The enclosed internetwork volume is free of kilogauss fields but does contain isolated patches of 500 Gauss field that may consist of weaker fluxtubes (Lin, 1995; Solanki *et al.*, 1996), isolated patches of weaker horizontal field (Lites *et al.*, 1996) which are perhaps a subclass of field structures with all sorts of inclinations (Meunier *et al.*, 1998), and possibly a truly weak diffuse field. The main structuring in the deep photosphere is the shallow granulation pancake pattern caused by radiative losses from convective upwellings. Deep downflow fingers marked by long-lived "intergranular holes" may produce "acoustic events" (Restaino *et al.*, 1993; Rimmele *et al.*, 1995; Roudier *et al.*, 1997; Hoekzema *et al.*, 1998a) in the middle photosphere, which is otherwise dominated by the 5-minute oscillation, the interference pattern of the multitude of solar p-modes. Higher up the higher-frequency components gain dominance and contribute to the K_{2V}-grain producing acoustic shocks (Rutten and Uitenbroek, 1991; Carlsson and Stein, 1997). These have also been diagnosed in rocket spectrograms (Hoekzema *et al.*, 1997) and are now seen very well, again as bright internetwork grains, in the TRACE 160 nm images at `http://vestige.lmsal.com/TRACE/Public/FirstLight/`. The occurrence of the brightest of these shock-produced internetwork grains is here attributed to pistoning by strong subsurface downflows; if so, the TRACE 160 nm image sequences may provide input piston sites for local helioseismology (Duvall *et al.*, 1993). The shocks may also excite canopy waves (Hoekzema *et al.*, 1997) that may funnel down into the network tubes (Deubner and Fleck, 1990) and may have to do with the FIP fractionation (Rutten, 1997). Scales: fluxtube diameters 0.1–0.2$''$, granule diameters 0.5–1.5$''$, five-minute oscillation patches 5–15$''$, three-minute shock patches 1–3$''$, internetwork cell sizes 20-40$''$, canopy heights unknown.

the Ca II H_{2V} and K_{2V} grains form, and indeed point at the presence of shocks (Rutten and Uitenbroek, 1991; Carlsson and Stein 1994, 1997; cf. Rutten 1994, 1995). In contrast, the magnetic network does not show any hint of the fast modes expected to travel up along or in fluxtubes to heat the upper atmosphere. The measurements so far show only long-period modulations, five-minute and longer, that may betray erratic footpoint swaying rather than specific wave modes (cf. Kneer and Von Uexküll 1983, 1985, 1986, 1993; Lites *et al.*, 1993).

4. Lower Atmosphere: Photospheric Composition

To what extent do the inhomogeneous phenomena sketched in Fig. 3 upset the use of the simple temperature stratification sketched in Fig. 2 for abundance determination? This issue is addressed by Solanki (1998) and Grevesse and Sauval (1998) in their reviews. Its outcome is summarized by two dedicationally named equations:

Holweger: $\mathrm{PPSA} + \mathrm{HOLMUL} + \mathrm{LTE} + \xi_\mu + E(\gamma) + gf \Longrightarrow A_{12}^{\odot}$

Grevesse: $A_{12}^{\odot} = A_{12}^{\mathrm{M}} - 0.004.$

The Holweger equation states that the proper recipe to derive solar abundances is to assume a plane-parallel solar atmosphere obeying the HOLMUL temperature stratification hydrostatically and to assume LTE, a best-fit microturbulence value ξ_μ and a best-fit van der Waals damping enhancement factor $E(\gamma)$. The only remaining uncertainty is the transition probability gf (cf. Kostik *et al.*, 1996). The point is proven by the Grevesse equation which states that for any element, excepting the lightest and carbon, the solar abundance determined Holweger-wise equals the value from carbonaceous chondrites, with a negligible correction for gravitational settling derived from fitting p-mode frequencies. Grevesse and his colleagues have proven the validity of this equation over and over again, validating the first equation as well. They represent a great boon for stellar abundance determination practitioners: forget about granules, waves, shocks, fluxtubes and NLTE complications in photospheric composition studies!

5. Lower Atmosphere: Speculative Connections

Finally the two dotted arrows in the rightmost column of Fig. 1. They belong to the future, so I will just mention them as speculations — to be taken as insights when correct. They concern the internetwork shocks that are evidenced by Ca II and TRACE internetwork grains. The first point is that the shocks may be connected to subsurface phenomena (Hoekzema *et al.* 1998a, 1998b, 1998c). It isn't clear yet whether the grains selectively prefer locations with special pistoning properties. A long debate on a magnetic connection seems to end negatively (Lites, Rutten and Berger, in preparation); it seems more likely that the presence of particularly bright “grain trains” betrays fast subsurface downflow plumes. If so, observed grain occurrence may supply useful input constraints to local helioseismology, specifying where the major acoustic sources are.

The second point is that the interactions between shocks and canopies may contribute to FIP fractionation (Rutten, 1997; cf. review by Judge and Peter, 1998). In general, the fractionation must occur where hydrogen is predominantly neutral, yet at a height where the collision frequency is low enough to permit some uncoupling between particle species, and requires motion across field lines so that line-tying constrains the charged particles. The ubiquitous internetwork shocks provide the highest velocities in the low chromosphere (up to 10 km s^{-1} in the post-shock downfall phase) at the lowest densities reached by non-magnetized plasma. And at some height they must interact with a canopy-like transition to field domination. This seems a highly likely site for sieving out charged particles. The amount of sieving then depends on canopy geometry and should favor closed-field regions.

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