Journal of Physics and Astronomy

Research | Vol 10 Iss 9

Core to Solar Wind: A Stepwise Model for Heating the Solar Corona

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Received date: 13-September-2022, Manuscript No. tspa-22-74433; **Editor assigned:** 15-September-2022, PreQC No. tspa-22-74433 (PQ); **Reviewed:** 23-September-2022, QC No. tspa-22-74433 (Q); **Revised:** 24-September-2022, Manuscript No. tspa-22-74433 (R); **Published:** 30-September-2022, DOI No. 10.37532/2320–6756.2022.10(9).297

Abstract

The model outlined here embodies three distinct, successive processes which both define and characterize the Sun's chromosphere, transition region and corona. Operating experience from fusion research shows how Spitzer resistivity may render ohmic heating in the chromosphere self-limiting and thus serve to define the lower margin of the transition region; its upper margin is at ~ 6.10^3 K, where radiative cooling of He/H plasma decelerates sharply. The third and last stage in the proposed scheme is expansion into the tenuous plasma of space, which leads to the acceleration of ions to high energies, long recorded by spacecraft instruments as He^{++}. There is thus dynamic continuity all the way from the solar interior - the energy source for spinning columns in the Rayleigh–Bénard setting of the convection zone - to the coronal exhalation of the solar wind, a finding which should benefit the analysis of space weather, witness the association between helium in the solar wind and the incidence of coronal mass ejections.

Keywords: Sun; Photosphere; Chromosphere; Transition region; Corona

Introduction

The high temperature (≥ 1 to 2.10^6 K) of the Sun's outermost atmosphere or corona was identified in 1939 but has still to be explained. The mechanisms currently most in favour emphasize magnetic reconnection or waves of some kind and they treat the chromosphere and corona together [1]. This paper develops an alternative scheme which links the Sun's interior with its atmosphere in three stages corresponding to (and indeed identifying) the photosphere-chromosphere, the transition region and the corona [2].

Bearing in mind that any analogy between processes on the Sun and in terrestrial laboratories particularly fusion is only approximate, there are instructive parallels between the first step in our model and the early stages of a conventional tokamak operation especially as laboratory experiments for these conditions are not available [3]. There a toroidal current serves the dual purpose of confining the plasma and heating it. As the main contours of the solar body represent the interplay between gravitational contraction and thermal expansion, the solar environment performs confinement effectively though imperfectly, thus freeing the available magnetic energy from this task. In fact, as indicated by the solar wind, there is a net surplus of plasma to sustain the chromosphere.

Citation: Vita-Finzi C, Core to Solar Wind: A Stepwise Model for Heating the Solar Corona. J. Phys. Astron. 2022;10(9):297.

Step 1

Plasma composition as well as induction heating shows qualified kinship between Sun and laboratory, although in a tokamak the favoured fuel deuterium-tritium is fully ionized at the temperatures required for fusion (c 10^8 K). The H:He ratio may dominate discussion of the influence of elemental abundance on chromospheric heating, with a photospheric bulk composition of H 90.965% and He 8.89%. Sodium, magnesium, calcium, and iron are also present, a fact that is exploited in particular in the assessment of fractionation between the photosphere and different varieties of solar wind [4]. The impurities that have been detected during the ohmic heating phase of JET operation, such as reactor wall material (Ni, Cr, Fe), oxygen, carbon, molybdenum and chlorine, lead to radiation losses and presumably do so in the solar reactor [5].

The accepted view is that the temperature of the chromosphere rises from 66.10^2 K at its contact with the photosphere to ~ 3.10^4 K over a distance of ~ 25.10^5 m [6]. In our proposed tripartite scheme the weakly ionized Hα of the chromosphere is subject to ohmic (or Joule) heating. In accordance with the account by Spitzer the resistance and thus the efficacy of ohmic heating decrease in proportion to the electron temperature as $T_e^{-3/2}$ a, so that there is a point at which ohmic heating stalls [7]. Owing to operational constraints ohmic heating at startup in most tokamaks can attain at most~1 keV, say 10^7 K, as is the case with the JET tokamak [8,9].

It has been suggested that the temperature of the chromosphere 'steadfastly refuses to rise above 10^4 K until hydrogen becomes fully ionized' perhaps because 'ionization of hydrogen leads to a high specific heat' [10]. The issue of specific heat had previously been raised in a study of the Jovian atmosphere for which an atmospheric composition of hydrogen and helium was postulated [11]. A non-dimensional plot of specific heat against temperature at 1- 6.10^4 K for particle densities from 10^{10} gcm^{-3} to 10^{-6} gcm^{-3} and for hydrogen unit volumes of 0.333 and 1.0 (equivalent to 50% and 100% hydrogen by volume) yields two prominent peaks **FIG. 1**. The greater is at 2.5 to 4.10^4 K, which may be manifested as a heightened but short-lived response to ohmic heating when the transiting gas attains a critical temperature. This specific heat imposes an upper limit on the chromospheric temperature well below the Spitzer limit. Indeed, the temperature in the Sun, after a temporary reversal, increases only to ~ 2.10^4 K some 3.10^3 km above the photosphere.

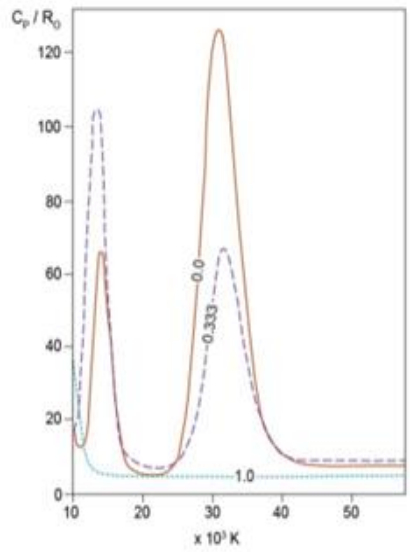

FIG.1 **Plot of specific heat against temperature at 1-6.10^4 K for particle densities from 10^{-10} to 10^{-6} g cm^{-3} and for hydrogen unit volumes of 0.333 and 1.0 equivalent to 50% and of 100% hydrogen by volume [11]**.

In our model of the Sun, induction is by way of electromagnetic energy derived from spinning convective pseudo-Taylor columns in the Rayleigh-Bénard setting of the convection zone - pseudo in the sense that they may develop in a fluid subject to strong rotation and thermal forcing although without the basal obstacle of the original definition [12-14]. Large-scale vortices are a possible outcome of rotating planar convection in an electrically conducting Boussinesq fluid [15]. The associated dynamos generate magnetic fields that are concentrated in the shear layers surrounding the vortices, although for Rayleigh numbers just above a critical value the convection takes the form of elongated columns with a small horizontal cross-section and is aligned with the rotation axis [16]. These are the structures that govern photospheric granulation [2].

The columnar model evidently differs from the classic notion of a primarily convective mechanism for granulation [17]. The summit of the columns is manifested as mesogranulation and supergranulation; the surface flow field is accordingly in close agreement with the magnetic field [18]. The columns are free to spin, even if closely packed because they are insulated mechanically by sheaths [19]. Indeed, Spacelab-2 white-light images illustrate both clockwise and anticlockwise spin; they also show that photospheric vorticities can twist a magnetic flux tube by 360° in < 3 hours, that is an average of > 2°/min [18]. Tangential (vertical) flows associated with the average supergranule outflow are indeed reported to reach about 10 m s^{-1} [20].

The fluid uppermost photosphere in which they spin is partly ionized and therefore electrically conducting. The cylindrical support is irrelevant except insofar as it creates quasi-regular spacing of planar rotating discs at the photospheric surface. Large-scale-vortex dynamos, which call for magnetic Reynolds numbers ~100 to 550, are here proposed as the source of basal chromospheric heating [21,22]. An analogy with the H/He atmospheric evolution of young terrestrial planets points to XUV radiation as a plausible supplementary heating source [23]; XUV emission by the upper chromosphere and the TR was demonstrated by a slit spectrograph observation from Skylab [24].

Magnetic energy flux at the photosphere has been evaluated at active regions, such as NOAA 11158, by modelling complemented by Hinode satellite observations [25]. At one plage region the vertical Poynting flux had values of about $5 \pm 1 \times 10^7$ erg $cm^{-1}s^{-1}$, close to the energy loss (~2×10^7 erg $cm^{-2}s^{-1}$) estimated for active-region fields in the chromosphere [26,27]. The dominant heating mechanism, one of three discussed by Goodman, is resistive dissipation of the proton (Pedersen) currents driven by the convection electric field that we have visualized as spinning columns [28].

Indeed, the modelling by Goodman leads to the proposition consistent with the theme of this paper that the chromosphere of the Sun (away from flaring regions) is *created* by Pedersen current dissipation [29]. Heating by Pedersen current dissipation is very inefficient when the plasma is fully ionized and strongly magnetized, somewhat above ~2170 km, consistent with the value of 2500 km for the lower boundary of the Transition Region cited earlier [30,6].

Step II

In a preliminary version of the tripartite scheme, the Joule-Thomson (J-T) effect was put forward as the pertinent heating system for the transition region though without the throttling that was included in the classic experiments by Thomson & Joule (1853) [2,31]. In the absence of experimental data for the temperatures at issue the term J-T is provisionally retained for the heating of a H/He plasma which is associated with a reduction in electron density n_e from ~ 10^{19} to 10^{15} m^{-3}, that is to say when a strong negative density gradient in the quiet Sun coincides with a strong positive temperature gradient [32].

In a widely reproduced diagram**,** the onset of the TR corresponds to a plasma particle density *N* (as distinct from 'plasma density'

commonly used to signify electron density) of slightly more than 10^{16} m^{-3} **FIG. 2** [33]. Photoionization of hydrogen reduces its cooling efficiency by some six orders of magnitude so that at high temperatures (10^4-10^8 K) neutral hydrogen cools at about 10^{-18} erg cm^3s^{-1} compared to 2.10^{-24} erg cm^3s^{-1} for ionized hydrogen, with a peak (to judge from the published data) at ~ 10^3 K [34]. Photoionization has a similar effect on helium, which when partially ionized cools very efficiently by blackbody radiation and direct coupling to the helium Lyman continuum [35]. Once fully ionized by further heating, however, it no longer couples well to the continuum (the Lyman limit being 91.2 nm, 13.6 eV). This signals the end of radiative loss or, in other words, the onset of uninhibited heating, and temperatures of 10^6 K are rapidly attained. In short, the trigger is more in the nature of a safety catch which is released at a critical temperature.

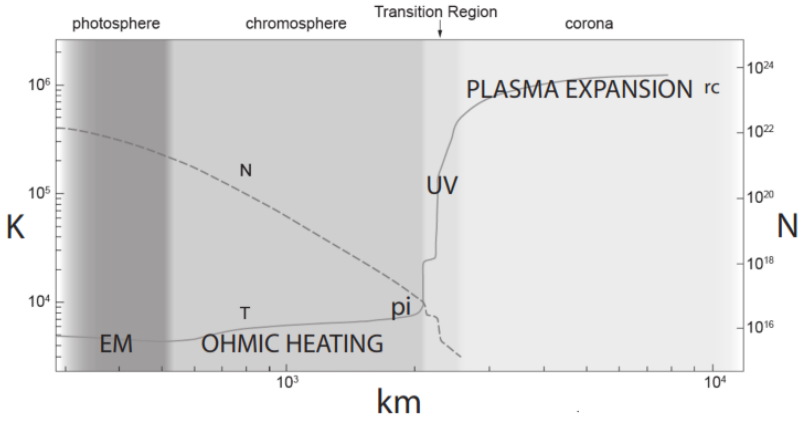

FIG. 2 **Proposed heating episodes and the intervening triggers set against major subdivisions of the solar atmosphere and plots of temperature (T) and plasma particle density (N). EM = electromagnetic energy, pi = photoionisation, rc = radiative cooling; T and N after [33].**

A value of ~ 6.10^3 K signals the region where cooling by radiation begins to nullify EUV heating as shown by radiative cooling functions for $^3HeH^+$ and $^4HeH^+$ **FIG 3** [36]. Here the rate of cooling attains between 10^{-10} to 10^{-9} erg/s. Indeed the calculated radiative cooling function (in erg $cm^{-3}s^{-1}$) at temperatures > 10^4 K for plasmas at low densities with solar abundances in collisional ionization equilibrium K drops rapidly from 10^5 to $10^{7.5}$ K [37].

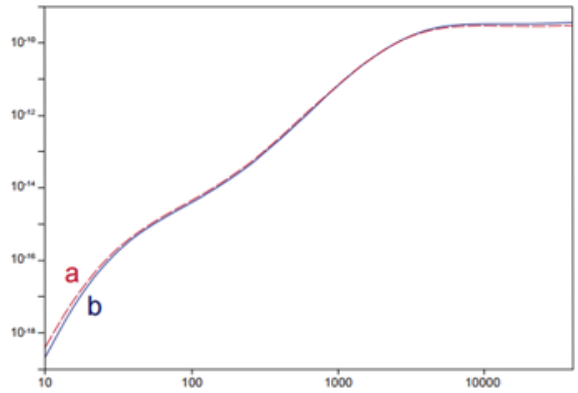

FIG. 3 **Radiative cooling function (erg/s) of HeH plasma [36]. a = $^3HeH^+$, b = $^4HeH^+$**

Step III

The upper limit of the TR may be defined as about 5.10^6 m above the photosphere by a deceleration in the temperature increase than in progress. Thereafter heating, triggered by propinquity to the near-vacuum of space, continues equably. Gurevich *et al*. and Gurevich & Pitaevsky were perhaps the first to show that the expansion of a plasma into a vacuum or a more tenuous plasma could result in the acceleration of ions to high energies, a process for which the self-similar solution indicates a logarithmic increase in velocity [38-41,23]. Plasma expansion has been investigated experimentally as well as theoretically even though the circumstances that concern us here, viz. temperatures of 10^6 K and coronal pressures of perhaps $1.3\ 10^{-11}$ Pa, present even more serious laboratory limitations than does the ohmic heating of plasmas in the chromosphere [42,43]. But heating of He^{++} ions in the solar wind has long been recorded by spacecraft [44].

The bearing of this effect on space phenomena was made explicit by the interaction of an obstacle with a plasma. Relation between pressure fall and temperature in an astronomical context was assumed by Kothari when he showed that, for a relativistically degenerate gas (i.e. one nearing its ground state) undergoing Joule-Thomson expansion, the degree of heating per unit fall of pressure increased with the degree of degeneracy [45]. Samir & Wrenn reported that ionospheric electron temperature measured by a Langmuir probe in the near wake of an artificial satellite (Explorer 31) was raised above that of the ambient electron gas by as much as 50% [46]. They referred to earlier work on the Gemini/Agena spacecraft in which wake temperature was 1700 K greater than the ambient temperature in one experiment and 764 K in another [47]. The Moon's wake provided scope for related work; the increase in the electron temperature in the lunar wake found by the SWE plasma instrument on the WIND spacecraft amounted to a factor of four although ion temperatures were little changed [48]. Laboratory investigations based on immersion of a plate in a single-ion, collisionless, streaming plasma, saw 'early time expansion' result in ion acceleration into the wake [49].

Conclusion

Contrary to the accepted puzzling notion that the transition region and even the chromosphere are heated inwards from the corona, the temperature rise is cumulatively radial. What is more, structuring the solar atmosphere into three major zones is not the source of our stepwise heating sequence but its outcome.

The coherence between solar wind variations and sunspot activity **FIG. 4** is consistent with our proposed tripartite heating scheme: induction heating, which brings temperatures up to 20,000 K and triggers Joule-Thomson heating, which in turn results in temperatures of 250,000 K at the transition region, and thereafter plasma expansion into the near vacuum of space, which is here proposed as the mechanism by which temperatures of 1-2 million K are raised in the corona before it grades into interstellar space.

The long-term record of the Sun's activity, essential for robust interpretation of paleoclimates as well as for assessing the solar factor in weather, requires detailed information on the source of EUV fluctuations. Measurements by the EVE instrument on the Solar Dynamics Observatory satellite combined with neutrino data suggest that the UV flux is modulated primarily by rotation of the solar interior (provisionally named the Dicke Cycle) rather than the passage of active areas across the solar disc. Thus periodicities recorded by cosmogenic isotopes such as ^{10}Be, which respond to oscillations in the strength of the solar wind, are better guides to the solar factor than observed sunspot records and have the advantage of spanning $> 10^5$ yr rather than a mere 4.10^2 yr. In short, solar wind emerges as the one dependable indicator of solar activity. Sunspot data are compromised by their indirect relation to the Sun's irradiance: the rotation of active areas reportedly explains no more than 42% of its variation.

The proposed scheme could help to explain heating in other bodies (such as Titan) which display a radial increase in temperature and a decrease in plasma density as well as sustained gas outflow. It may also bear on the thermal evolution of other coronal stars.

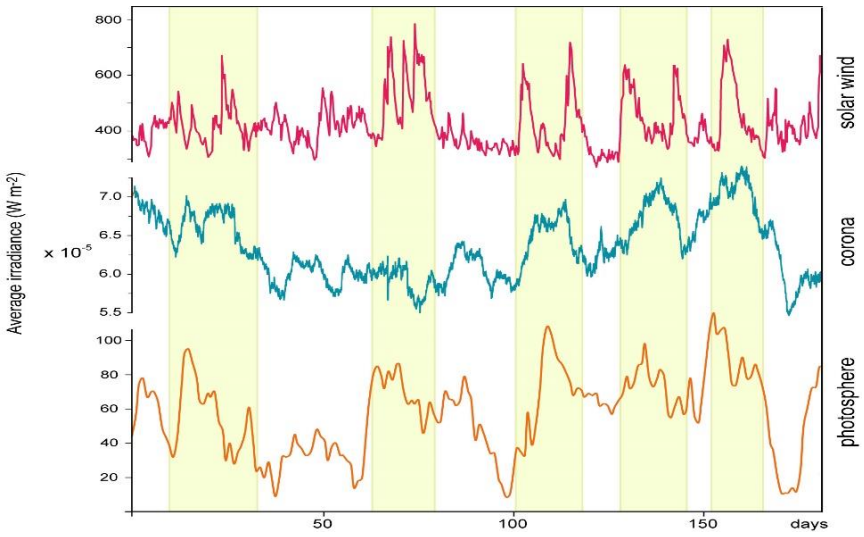

FIG. 4 **Irradiance variation for 1 Jan-1 July 2012 for the photosphere, the solar corona, and the solar wind. Plots and scale details (W m-2) in [2].**

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