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Coronal heating: analogous processes in stellar and galactic media

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Abstract. Coronal plasmas of high temperature (10^6 K and more) have been confirmed now to exist not only around stars like the Sun, but also around the planes of galaxies - including our Milky Way and even extragalactic systems. Structural similarities exist between stellar atmospheres comprising coronae and transition zones and the dilute plasma around galaxies.

In this paper the heating of these plasmas is proposed to be partly caused by collisional dissipation of fast particles, which are able to overcome the lower layers of the solar chromosphere or, correspondingly, those near a galactic plane. The production of fast particles heating the coronal plasmas may have a multicausal origin which is not considered here in detail.

In the case of the Sun, the transition zone between the photosphere ($T < 10^4$ K) and the corona ($T > 10^6$ K) is well investigated by earlier observations, e.g. in the visible and UV spectral ranges. On the average, the strong gradients of temperature (positive) and density (negative) are stationary. They can be explained by the assumption of a balance between, on the one hand, a steady flow of suprathermal particles (kinetic energy $E_{\rm k}$) outward with a spectral energy distribution density $N(E_{\rm k}) \propto E_{\rm k}^{-(3\div4)}$, and, on the other hand, an energy loss which is mainly due to radiation.

As to our Galaxy, the transition between the neutral hydrogen (HI) layer near the plane (scale height about 130 pc) and the outer "halo" region f is not well known. But the existence of fast particles, even relativistic ones, is proved by their gyro-synchrotron radiation. Moreover, by the observations of *ROSAT*, an X-ray emitting Galactic corona is indicated (similarly "patchy" as the solar corona). The assumption is justified that, in larger dimensions and in a plane geometry, gradients in temperature and density onto this Galactic corona exist. Using the observed scale heights of neutral HI and of free electrons, a rough calculation for the slope of temperature and electron density is possible with the aid of Saha's equation.

Key words: plasmas – Sun: transition region – ISM: general – Galaxy: halo

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1. Introduction

Recently it has become clear that the phenomenon of hot coronae around cosmic central bodies is not only restricted to the Sun and stellar objects, but also to galaxies and even extragalactic systems (cf., e. g., Bregman 1988). Elliptical galaxies can possess as much as 10^{10} solar masses of about 10^7 K plasma (Forman et al. 1985). Concerning our Galaxy it is obvious that a one-million K gas is surrounding the galactic disk (Nousek et al. 1982). Although the production of hot gas in stars and galaxies may be quite different, similarities in the structure and dynamical evolution of coronal plasmas in different objects are apparent and will be discussed in the present paper. In particular, this holds for the formation of a scale-dependent inhomogeneous temperature gradient (transition region), and the generation of winds and mass ejections.

Treating the formation of coronae, the identification of gain and loss processes of coronal energy is of basic interest. Concerning the gain of energy, three basic processes may be noted leading to heating of a coronal plasma:

a) Heating by waves (acoustic and/or Alfvén waves, shock waves),

b) magnetic reconnection,

c) Coulomb interactions of fast particles (collisional heating).

The possibility a) has been discussed extensively since many years. Narain & Ulmschneider (1990) have pointed out that the damping of acoustic and Alfvén waves is so strong that an essential release of thermal energy is limited to the chromosphere, but cannot reach the upper transition zone or even the corona. Magnetic reconnection and electric currents certainly play a role as heating mechanisms in all regions with (time- and space-) variable magnetic fields. On the Sun, in particular, this process may act during the active phase of the solar cycle mainly referring to coronal regions with closed magnetic fields (cf., e.g., Kliem & Karlický 1999).

But, following Kuperus et al. (1981), some restricting constraints hold for the stationary heating by reconnection, and so it is probably not the unique source of coronal heating on the Sun. Recently, reconnection is considered also in the interstellar medium (at the edge of "high velocity clouds") of our Galaxy (Kerp et al. 1994), but here the same constraints have to be considered.

Nevertheless, magnetic reconnection may act as a source of suprathermal particles also in the Galaxy (Zimmer 1996).

The third point c) seems to be widely ignored in the literature, as was mentioned by Haerendel (1987).

Somewhat later, however, interesting approaches were given by the "velocity filtration model" claimed by Scudder (1992a, b; 1994), and by Estel & Mann (1999).

In the present paper, an attempt is made to establish collisional heating as a noticeable process on the Sun and in the interstellar medium (ISM) outside galactic planes, as well. As to the stationarity of coronae, the balance of gain and loss of coronal energy has to be discussed.

2. Thermalization of fast particles in the solar plasma

In order to discuss the energy input of fast particles, several time- and length-scales characterizing interactions are available (cf. Spitzer 1956). One relevant relaxation time scale, t_E, describes the loss of kinetic energy $E_\mathrm{k} = mv^2/2$ of (non- or weakly relativistic) "test" particles of velocity v, which collide with "field" particles (subscript "f") in a hot plasma:

$$t_E \propto v^3 n_\mathrm{f}^{-1} \,. \tag{1}$$

Hence, the corresponding length scale (free path) L_E is given by

$$L_E = t_E v \propto v^4 n_\mathrm{f}^{-1} \,. \tag{2}$$

n_f is the number density of the field particles. The factor of proportionality, in general, contains slowly varying terms such as the logarithmic Gaunt factor. Inserting $T_\mathrm{f} = 10^5$ K, $n_\mathrm{f} = 10^{10}\ \mathrm{cm}^{-3}$, and $v = 30$ km/s, the scale length L_E is of the order of 10 m.

When $v = 300$ km/s (at the same T_f and n_f), L_E becomes 1000 km and more (Hirth & Krüger 1995). In a pure thermal plasma (for example that of the field particles) v^2 can be replaced by kT/m in Eqs. (1) and (2) to get the "self-collision time" and the "mean free path" L_M of the plasma particles, respectively. The latter is

$$L_M \propto T^2 n^{-1} \,. \tag{3}$$

Thus, fast particles starting in the lower chromosphere (in z-direction upwards), can reach the corona before loosing essential parts of their kinetic energy by collisions.

The transition region, having a mean thickness of the same order (few 1000 km), therefore appears as a shock front or, better, as a front of rarefaction (Linhart 1960).

Within this region the temperature enormously increases with a gradient of the order hundred K/km. Similarly sharp is the negative gradient in the number density n.

Particles whose velocity v is larger than the local value of $(2kT/m)^{1/2}$ can continue their way. After the time t_E (cf. Eq. (1)) their kinetic energy has decreased to a value of, say, E_k/α, where α is of the order 2. When this value is equivalent to the local $kT(z)$ of the ambient medium, we can say, the particles are thermalized.

3. The gradients of temperature and density on the sun and the spectral energy distribution of fast particles

The slope of $T(z)$ and $n(z)$ in the solar transition region is roughly known (cf., e.g., Bray & Loughhead 1974; Golub & Pasachoff 1997):

$$T = T_0 \exp(+z/z_T) \,, \qquad 1/z_T \simeq 6.1 \times 10^{-4}\,\mathrm{km}^{-1} \,, \tag{4}$$

and

$$n = n_0 \exp(-z/z_n) \,, \qquad 1/z_n \simeq 6.5 \times 10^{-4}\,\mathrm{km}^{-1} \,. \tag{5}$$

On a linear scale, at about 7600 km above the photosphere, the gradient $\mathrm{d}T/\mathrm{d}z$ is of the order 20 K/km, and increases rapidly to several 100 K/km. (Of course, approaching the corona, the gradient again flattens).

Consequently, a relation can be established between E_k and that $T(z)$ (or $z(T)$), where thermalization occurs:

$$z \simeq \ln\left(E_\mathrm{k}/(2kT_0)\right) z_T \,, \qquad \mathrm{d}z = \mathrm{d}E_\mathrm{k}/E_\mathrm{k} \,. \tag{6}$$

We should note that, in general, the solar gravity with

$$g_\mathrm{sol} = 2.74 \times 10^4\ [\mathrm{cgs}]$$

can be neglected as a decelerating force for the test particles. With $N(E_\mathrm{k})[\mathrm{s}^{-1}\mathrm{cm}^{-2}\mathrm{erg}^{-1}]$ we can assume that a number of $N(E_\mathrm{k})\mathrm{d}E_\mathrm{k}[\mathrm{s}^{-1}\mathrm{cm}^{-2}]$ test particles are thermalized in the layer at height z, thickness $\mathrm{d}z$, and temperature $T(z)$. Then, in a stationary state, this gain of thermal energy must be compensated by an energy loss. In this instance radiation (P_rad) is adopted as main loss:

$$P_\mathrm{rad} \propto n^2 T^\alpha\ [\mathrm{erg\ s}^{-1}\mathrm{cm}^{-3}] \,. \tag{7}$$

Heat conduction is neglected, in accordance with Narain & Ulmschneider (1990), who estimated that thermal conductivity is insufficient to maintain equilibrium.

Indeed, radiation losses are the major energy loss at least in the upper transition region and corona. The loss by heat conduction may be of some importance in the lower transition region and in the chromosphere where the temperature gradient is steepest. In general, however, heat conduction is strongly reduced by the magnetic fields, except for open regions. The change of the heat flux W is

$$\mathrm{d}W/\mathrm{d}z \approx \alpha 10^{-6} T^{5/2} \mathrm{d}^2 T/\mathrm{d}z^2 \,, \tag{8}$$

where α is a correction factor due to the magnetic field, $\alpha = [1 + (\nu_H/\nu_\mathrm{c})^2]^{-1}$, where $\nu_H = 2.8 \times 10^6 H$ [Hz] is the electron gyrofrequency and ν_c denotes the electron-ion collision frequency. With $T = 10^6$ K, $\mathrm{d}^2T/\mathrm{d}z^2 = 10^{-10}[\mathrm{K\ cm}^{-2}]$, $\nu_H = 2.8 \times 10^6$ Hz ($H = 1$ G), $\nu_\mathrm{c} = 10$ Hz, we have $\mathrm{d}W/\mathrm{d}z \approx 10^{-11}[\mathrm{erg\ cm}^{-3}\mathrm{s}^{-1}]$. On the other hand, taking $\alpha = 1/2$ for an ionized gas in Eq. (7), the radiation loss of a fully ionized gas P_rad is of the order $P_\mathrm{rad} \approx 10^{-27} T^{1/2} n_\mathrm{e}^2 \approx 10^{-6}[\mathrm{erg\ s}^{-1}\mathrm{cm}^{-3}]$, if T again is 10^6 K and $n_\mathrm{e} = 10^9\mathrm{cm}^{-3}$.

Thus, the balance between the input of thermalized kinetic energy and the radiation loss writes:

$$N(E_\mathrm{k})\, E_\mathrm{k}\, \mathrm{d}E_\mathrm{k} \propto n^2 \sqrt{T}\, \mathrm{d}z\ [\mathrm{erg\ s}^{-1}\ \mathrm{cm}^{-2}] \,. \tag{9}$$

Inserting from Eqs. (4), (5), and (6) into relation (9) yields

$$N(E_{\rm k}) \propto E_{\rm k}^{-[(3/2)+2z_T/z_n]} \, . \quad (10)$$

When $z_T/z_n = 1$, the exponent in Eq. (10) is $\gamma = -3.5$. We should note here that the function T^α in Eqs. (7) and (9) must be modified when line emission plays a noticeable role in the cooling process. A rough approximation would be $\alpha = -1/2$ so that $P_{\rm rad}$ is proportional to $N^2 T^{-1/2}$. Actually, the T-dependency of $P_{\rm rad}$ is more complicated than the approximations used here. The cooling by lines is more effective at temperatures less or about 10^5 K, while free-free radiation ($P_{\rm rad} \propto T^{1/2}$) becomes noticeable at about 10^6 K.

4. The Galactic counterpart: HI-layer, transition zone, and galactic "halo"

The similarity in the temperature structures of the solar atmosphere and the gas around galaxies is evident primarily from a phenomenological point of view: Near the Galactic plane, there is relatively low temperature and neutral HI, confirmed by its observable 21 cm line emission. In the Galactic "corona", far away the Galactic plane, we have high temperature gas of at least 10^6 K as confirmed by the observation of X-ray radiation in the keV range.

Since suprathermal particles, even relativistic ones, can be proved by their synchrotron emission, it is reasonable to assume, analogously to the Sun, collisional heating of the Galactic corona, too.

The existence of relatively high temperature gas and, consequently, an increase of temperature perpendicular to the Galactic plane, was already proposed by Spitzer (1956). He claimed a pressure equilibrium between relatively cold, dense clouds and hot, ionized gas around, but neglected magnetic fields. The scale height of the hot gas ($T = 10^6$ K) was estimated to about 8 kpc.

The discussion on the stability of the halo is not yet finished. Pikelner & Shklovsky (1959) preferred a dynamical equilibrium for the halo, the gas having a moderate temperature. They introduced the interaction of cosmic rays, magnetic fields, and differential rotation to form a "halo-spheroidal" subsystem around the Galactic center.

Parker (1966) considered the stability of a hydrostatic equilibrium including magnetic pressure and the pressure of cosmic rays, or relativistic particles, respectively. He showed that this halo is stable on a time scale of about 10^7 yr.

Bloemen (1987) derived stable hydrostatic equilibrium configurations, too. In his model high temperatures (10^6 K) occur near the plane up to about 1 kpc from the plane, but intermediate temperatures within about 1 and 3 kpc distance from the plane. The scale height of the halo is quoted to > 5 kpc.

Although it is not our aim to join the stability discussion we will spend some remarks on this point in Sect. 5. Obviously there exist a stationary halo and also stationary gradients in temperature and density perpendicular to the Galactic plane (in z-direction).

There are many observations supporting the idea of a hot halo: The detection of lines of highly ionized atoms like C IV, Si IV, N V and others in absorption (cf. Savage & deBoer 1981; Savage & Massa 1987) show evidence of high temperatures of about 10^5 K at z-distances of about 1–3 kpc.

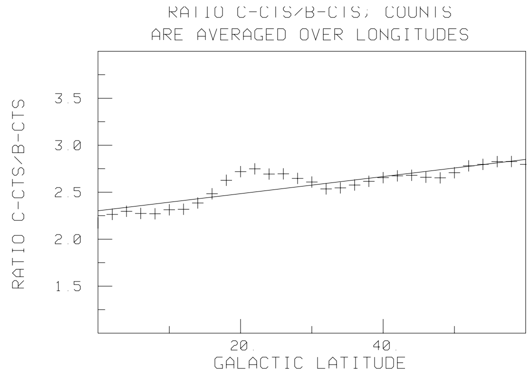

Fig. 1. Ratios of X-ray count rates of C-band over B-band in dependence of Galactic latitude.

As mentioned above, the analysis of *ROSAT*-observations (Hasinger et al. 1985; Snowden et al. 1991) support strongly the idea of a hot Galactic halo with at least 10^6 K.

Kerp (1994), on the base of *ROSAT*-measurements in the Draco region, derived a two-temperature model for the X-ray emitting plasma: Near the Galactic plane (local hot bubble) there is a temperature of nearly 10^5 K, and at least 10^6 K above the local ISM.

Even the elder observations, though with restricted spatial resolution, were yet sufficient to derive global features of the Galactic diffuse X-ray distribution. Consider, for example, C-band (cC in 0.13–0.28 keV) and B-band (cB in 0.08–0.16 keV) count rates as provided by the "Wisconsin-survey" (McCammon et al. 1983). If one averages the count rates in each band over all longitudes at any given Galactic latitude $b_{\rm Gal}$ and forms the ratio $r_{cC/cB} = \langle cC \rangle \, / \, \langle cB \rangle$, the latter shows a significant increase with growing $b_{\rm Gal}$ (cf. Fig. 1). The most simple interpretation of this correlation (Hirth & Moritz 1991) is to presume an increase of temperature with increasing height z (perpendicular to the Galactic plane).

Radio astronomical observations of diffuse bremsstrahlung and synchrotron emission show that both, suprathermal particles and even relativistic ones, are moving through the Galactic space. The relativistic particles are accelerated in pulsars and supernova remnants near the Galactic plane or by the Fermi process in moving magnetic structures.

So it is justified to assume that, similar to the Sun's atmosphere, the gradients in temperature (positive) and density (negative) are coupled with collisional heating by fast particles. They release energy, according to their initial kinetic energy and their free paths, in adequate heights of the halo.

The formula for the free path L_E of charged particles (Eq. (2)) shows that for moderate velocities of, say, v within $0.01c - 0.1c$, L_E can be of the order of several hundreds up to 1000 pc. Thus, the same arguments hold for the build-up of a positive temperature gradient in z direction as are used for the

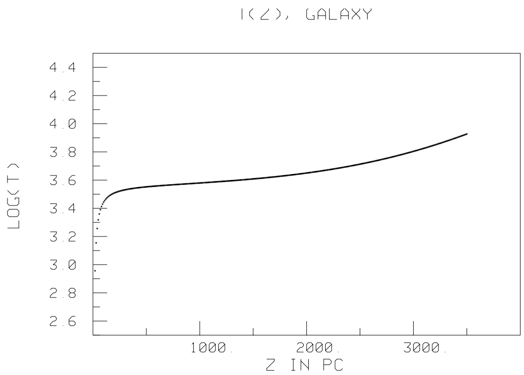

Fig. 2. Slope of T with Galactic height z, concluded from scale heights of $N_{\rm e}$ and $N(\rm HI)$.

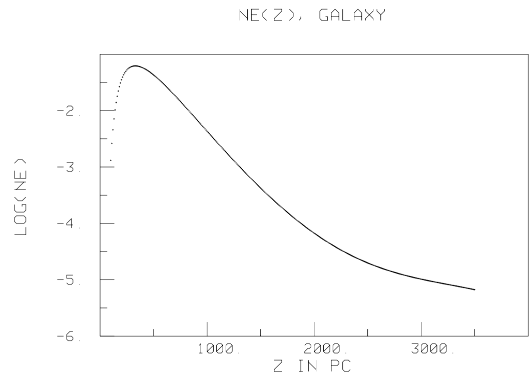

Fig. 3. $N_{\rm e}$ as function of height z compatible with the measurements of Readhead & Duffet-Smith (1975).

solar atmosphere. Hence only a vague estimate of the temperature gradient is possible.

On the one hand the neutral hydrogen (HI) has a scale height $z_{\rm HI}$ according to $n_{\rm HI} \propto \exp(-z/z_{\rm HI})$, with $z_{\rm HI} \simeq 135$ pc. In a good approximation the HI-density $n_{\rm HI}$ can be identified with that of the neutral component: $n_{\rm HI} \simeq n_0$, and therefore, $z_{\rm HI} \approx z_0$.

On the other hand, for the free electrons, $n_{\rm e}$, (and protons, when $n_{\rm e} \simeq n_{\rm p}$), a rough estimate of a scale height of $z_{\rm e} \simeq 500 - 600$ pc is provided by Readhead & Duffet-Smith (1975). The difference between the scale heights z_0 and $z_{\rm e}$ again proves qualitatively an increase of temperature in z-direction. We should note that the value of $z_{\rm e}$ represents a weighted mean including all concentrations of free electrons (SNR's, HII-regions), not only the uniformly distributed, diffuse gas we are interested in. The latter alone has a temperature of only about 100 K near the Galactic plane (derived from the HI-line observations) and hence a negligible degree of ionization. Thus, the proper scale height of diffusely distributed free electrons is probably much larger than 500 pc and cannot be simply described by a continuously decreasing exponential function of the kind $\exp(-z/z_{\rm e})$.

So, an increase of temperature with z can be concluded qualitatively. As just mentioned, the "clumpiness" of the electron density near the Galactic plane affects the scale heigth $z_{\rm e}$ and, consequently, that of the ratio $n_{\rm e}/n_0$.

In the following we will give an estimate for the slope of $T(z)$ of the diffuse gas. Its determination must have regard to the constraints just mentioned: The observed scale height z_0 is about 135 pc, the scale height $z_{\rm e}$ is extrapolated to 800 pc instead of 500 pc, and near the galactic plane ($z \approx 0$), T and $n_{\rm e}$ are about "zero".

Let us involve Saha's equation. We approximate the diffuse ISM by a pure hydrogen gas containing free electrons (number density $n_{\rm e}$), protons ($n_{\rm p}$) and neutral HI-atoms (n_0) and presume thermodynamic equilibrium. The H_2 and other molecules are due to the concentrated gas clouds. Saha's function $F_s(T)$ writes as:

$$\frac{n_{\rm e} n_{\rm p}}{n_0} = F_s(T) = (2\pi m_{\rm e} kT)^{3/2}\, h^{-3}\, \exp(-\chi/kT). \qquad (11)$$

A noticeable increase of F_s does not occur before T reaches about 3000 K. Using units of 10^4 K for the temperature (T_4), assuming $n_{\rm e} \simeq n_{\rm p}$, and inserting $n_0 = n_{\rm HI} = n_{00}\, \exp(-z/z_0)$, yields

$$n_{\rm e} = 4.91 \times 10^{10}\, n_0^{1/2}\, T_4^{3/4}\, \exp(-15.78/T_4)\ [\rm cm^{-3}]. \qquad (12)$$

By a trial and error procedure the following function $T(z)$ was found to be compatible with Eq. (12) and the constraints above:

$$T(z) = T_0\, \exp(z/z_2) + T_1\, \exp(-z_1/z), \qquad (13)$$

where $T_0 = 100$ K.

The fitted parameters are $T_1 = 3600$ K, $z_1 = 30$ pc, and $z_2 = 900$ pc (cf. Fig. 2). Via the second term of Eq. (13), in a formal mathematical analysis, $T(z)$ exhibits its first remarkable increase within the length of few hundred pc, where $T(z)$ grows from about zero to about 3000 K.

We should note that just in this region of z the diffuse gas is strongly disturbed by local, relatively hot and dense structures (SNR's, HII regions).Therefore, the slope of $n_{\rm e}(z)$ (of the electrons outside of the concentration mentioned) as expected shows a smooth maximum between 300 and 400 pc (cf. Fig. 3), which should not be overinterpreted, and decreases to about one half of the maximum after 800 pc as claimed before. Beyond the first few hundred pc $T(z)$ increases more moderately, approximated by an exponential law the scale height of which ($z_2 = 900$ pc) is not very certain.

Obviously, a remarkable temperature gradient is indicated. Extending the function to larger z, one finds $T_4 \simeq 10$ at $z \simeq$ 6 kpc, $T_4 \simeq 10^2$ at about 8 kpc. The characteristic scale height L_T for the increase of T of the diffuse gas can be estimated to, say, 500 pc.

We are aware that this simple consideration has little quantitative relevance, in particular at large z. Nevertheless, it seems remarkable that qualitatively Spitzer's (1956) result can be reproduced.

We note that the energy distribution of the Galactic relativistic particles (index of spectral energy $\gamma \approx -2.5$) deduced from the observed spectral index of the synchrotron intensity, differs from that of the suprathermal particles ($\gamma \approx$ -3.5 to -4.5).

Of course, comparing with the solar plasma, the representative Galactic parameters like number density and magnetic fields, are different by many orders of magnitude. Following Kirchner et al. (1994) and remembering Eq. (2) for the free path L_E, the small density of typically 10^{-2} to 10^{-3} cm^{-3} leads to $L_E^{(\mathrm{Gal})} \simeq 10^{12}$–$10^{13} L_E^{(\mathrm{Sun})}$, i.e. $L_E^{(\mathrm{Gal})}$ is of the order of 10^1–10^3 pc. Thus, the picture of fast particles accelerated in layers near the Galactic plane, flying in z-direction perpendicular to the plane and heating up the halo, seems as fruitful as in the solar atmosphere.

5. Discussion and conclusions

The existence of a hot-temperature Galactic halo appears sufficiently proved, as well from the observations as from theoretical aspects. What is not yet decided is the question, whether there is a stable hydrostatic equilibrium throughout the Galactic "atmosphere". This is preferred by Spitzer (1956), Parker (1966), and Bloemen (1987). A dynamical equilibrium was described by Pikelner & Shklovsky (1959). One should clear up the case of "hydrostatic equilibrium". Consider a neutral gas, horizontally stratified, under constant acceleration of gravity g in z-direction, with, for simplicity, only one species of atomic mass m starting without ionization. Then the equation holds

$$\frac{\mathrm{d}p}{\mathrm{d}z} = -\rho g \tag{14}$$

with $p = nkT$ and $\rho = nm$. As far as $T = T_0$ can be adopted as constant along z, we get the well-known hydrostatic equilibrium distribution

$$p = p_0 \exp\left[-\frac{mgz}{kT_0}\right], \tag{15}$$

the scale height being $h = kT_0/(mg)$, and $n/n_0 = p/p_0$. The index 0 refers to the values at $z = 0$.

It should be stressed once more that the linear relation between scale height h and T_0 only holds in a gas of uniform temperature, just T_0.

Now let us modify the situation by adopting $T = T(z)$. We put $n = n_0 \exp[-\varphi(z)]$ with $\varphi(0) = 0$. The function $\varphi(z)$ is rather arbitrary and its parameters can be adjusted by observations; they can be taken, in this sense, as free, predescribed parameters. The index "0" for N_0, T_0 now refers to the values at $z = 0$.

Instead of Eq. (14) we get

$$\frac{\mathrm{d}}{\mathrm{d}z}(kT) - kT\frac{\mathrm{d}\varphi}{\mathrm{d}z} = -mg\,, \tag{16}$$

$$p = n_0 kT_0 \left[1 - \frac{mg\psi(z)}{kT_0}\right], \tag{17}$$

and

$$kT = kT_0 \left[1 - \frac{mg\psi(z)}{kT_0}\right] \exp\psi(z) \tag{18}$$

with $\psi(z) = \int_0^z \exp(-\varphi(z'))\mathrm{d}z'$.

This means, if the mean thermal velocity $\sqrt{(kT_0/m)}$ exceeds the potential gh, the tail of the Maxwellian distribution provides a sufficient portion of suprathermal particles which is able to overcome the gravity near the solar photosphere or Galactic plane. These particles can move outwards to provide a positive temperature gradient in z-direction. Thus, this simple model gas already exhibits similar properties (with respect to the slope of $T(z)$) as the more complicated ionized gas treated above with Saha's equation. It is evident that the restriction of constant gravity g cannot be maintained at large z, and so the infinite increase of T is avoided.

With regard to the Galactic ISM it has become usual to introduce a generalized pressure consisting of the sum of "gas pressure" p_{g}, "cosmic-ray pressure" p_{cr}, and "magnetic pressure" $p_{\mathrm{m}} = B^2/(8\pi)$. Parker (1966) adopted fixed ratios between these pressure components, varying with z in the same way, while the gas was assumed isothermal with z. Instead of the simple thermal motion kT/m in Eq. (15), the term $\langle v^2 \rangle$ is introduced which includes also turbulent motions of statistically moving "eddies" in the ISM. This allows for the comparison with observables like the line width σ of HI, broadened by the Doppler effect.

In contrast to former approach cited above, we do not follow the isothermal approximation, because it is not compatible with the observational effects already described. As a consequence, we propose the introduction of a dynamical equilibrium. It is characterized by a steady flow of particles, partly thermalized according to their initial kinetic energy. The gain of thermal energy in any layer is balanced by radiation losses, so that stationarity is warranted.

Scudder (1994) used the nonthermal tails of modified Gaussian distributions to supply the solar-wind plasma. He claims the formation of the corona without heat addition. Such model seems to apply in particular for open field structures of the solar atmosphere.

Concerning the Galaxy, the most energetic particles, i.e. the cosmic-ray particles, are building up the Galactic halo or even partly leave the Galactic system.

It should be noted again that the model of collisional heating is not the only possibility for heating the Galactic or solar corona. In particular, heating by reconnection processes appears observable in the Sun's corona, as claimed, e.g., by Masuda (1994) and Masuda et al. (1994) also is anticipated for the Galaxy (cf. Birk et al. 1998). With respect to the Galaxy, the X-ray brightening occasionally visible at the edge of high velocity clouds is interpreted as caused by reconnection (Kerp et al. 1994). Nevertheless, the proposed model of collisional heating is compatible with all relevant observations from different frequency ranges and seems to provide an essential contribution of energy transfer.

The magnetic field mainly acts as a bond for the halo. In the regions with horizontal field direction it reduces the free path of charged particles (in z-direction) down to the gyro radius. It is generally accepted that the magnetic field near the Galactic plane is irregularly structured. Above few kpc height the field is predominantly horizontally directed, similar as loop structures in the solar corona. However, in the outer regions of the halo radial directions of the field become noticeable. In analogy to solar coronal holes and streamers, Galactic "chimneys" show the existence of discrete fast particle streams outward, as visible examples of plasma flows needed for collisional heating.

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References

Birk G.T., Lesch H., Zimmer F., 1998, Physica Scripta T74, 89.
Bloemen J.B.G.M., 1987, ApJ 322, 694.
Bray R.J., Loughead R.E., 1974, "The Solar Chromosphere", London.
Bregman J.N., 1988, in Pallavicini R. (ed.), Hot Thin Plasmas in Astrophysics, Kluwer Acad. Publ., 247.
Estel C., Mann G., 1999, A&A 345, 276.
Forman W., Jones C., Tucker W., 1985, ApJ 102.
Golub L., Pasachoff J., 1997, The Solar Corona, Cambridge Univ. Press.
Haerendel G., 1987, Proc. 21st ESLAB Symp, Bolesjö, Norway, ESA SP-275, p. 205.
Hasinger G., Schmidt M., Trümper J., 1985, A&A 246, L2.
Hirth W., Krüger A., 1995, Kleinheubacher Berichte 38, 1.
Hirth W., Moritz P., 1991, Kleinheubacher Berichte 38, 399.
Kerp J., 1994, A&A 289, 597.
Kerp J., Lesch H., Mack K.-H., 1994, A&A 245, L13.
Kirchner T., Hirth W., Krüger A., 1994, Kleinheubacher Berichte 37, 507.
Kliem B., Karlický. M., 1999, A&A, submitted
Kuperus M., Ionson J.A., Spicer D.S., 1981, ARA&A 19, 7.
Linhart J.G., 1960, "Plasmaphysics", North-Holland-Publ. Comp., Amsterdam, p. 152.
Masuda S., 1994, Ph. D. Dissertation, University of Tokyo.
Masuda S., Kosugi T., Hara H., Tsuneta S., Ogawara Y., 1994, Nature 371, 495.
McCammon D., Burrous D.N., Sanders W.T., Kraushaar W.L., 1983, ApJ. 269, 107.
Narain U., Ulmschneider P., 1990, Sp. Sc. Rev. 54, 377.
Nousek J.A., Fried P.M., Sanders W.T., Kraushaar W.L., 1982, ApJ 258, 83.
Parker E.N., 1966, ApJ 145, 811.
Pikelner S.B., Shklovsky I.S., 1959, Ann. d'Astroph. 22, 913.
Readhead A.C., Duffet-Smith P.J., 1975, A&A 42, 151.
Savage B.D., de Boer K.S., 1981, ApJ 42, 460.
Savage B.D., Massa D., 1987, ApJ 314, 380.
Scudder J., 1992a, ApJ 398, 299.
Scudder J., 1992b, ApJ 398, 319.
Scudder J., 1994, ApJ 427, 4469.
Snowden St., Mebold U., Hirth W., Herbstmeier U., Schmitt. J., 1991, Science 252, 1529.
Spitzer J. Jr., 1956, ApJ 124, 40.
Zimmer F., 1996, Dissertation, Uni. Bonn.