DOES H\(^{-}\) TRULY COOL THE SOLAR CHROMOSPHERE?

THOMAS R. AYRES

Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards, Boulder, Colo. 80309, U.S.A.

(Received 11 December, 1979; in revised form 11 March, 1980)

Abstract. I examine the controversial problem of H\(^{-}\) radiative cooling in the solar chromosphere. I find, in agreement with Praderie and Thomas, that H\(^{-}\) is a substantial source of radiative heating in the outer atmosphere, especially when departures from LTE are important. The role of H\(^{-}\) as a chromospheric heating agent must be considered carefully before net radiative cooling rates can be assessed from empirical chromospheric models, or calculations of nonradiative heating, for example by acoustic waves, can be pursued meaningfully.

1. Introduction

A heated controversy has developed during the past decade concerning the proper treatment of H\(^{-}\) radiative cooling in the solar chromosphere. The controversy began when Ulmschneider (1970, 1974) proposed a simple prescription for estimating excess radiative loss rates from empirical models. He contended that the apparent cooling rates by H\(^{-}\) in excess of those expected from an atmosphere in pure radiative energy balance (radiative equilibrium) are so large that the only viable heating mechanism to drive the chromospheric temperature inversion is the dissipation of short-period acoustic waves.

Subsequently, Praderie and Thomas (1972, 1976) criticized Ulmschneider's empirical chromospheric cooling estimates on the following grounds: (1) Departures from local thermodynamic equilibrium (LTE) in chromospheric H\(^{-}\) can depress the actual cooling rate significantly below the differential LTE recombination approximation prescribed by Ulmschneider. (2) Radiative losses in a particular species must be estimated from empirical models derived from observations of that species. (Ulmschneider and collaborators have, in some cases, derived H\(^{-}\) energy loss rates from empirical models based on spectral features, for example Ca II K and Mg II k, that have very different spatial averaging properties than the H\(^{-}\) continuum itself.) (3) The use of conventional radiative equilibrium models to assess photospheric and chromospheric energy balance can introduce systematic errors because the energy balance in H\(^{-}\) and strong Fraunhofer line cores is treated in LTE. Consequently, potentially important heating and cooling terms that arise from population imbalances in statistical equilibrium (nonLTE) are ignored.

Recently, the Praderie and Thomas/Ulmschneider controversy has continued with a series of rebuttals by Ulmschneider and Kalkofen (1978) and Kalkofen and Ulmschneider (1979).

The question of H\(^{-}\) cooling in the solar chromosphere is of fundamental importance. For example, several authors believe that short-period acoustic waves...
are the primary heating agent responsible for the chromospheric temperature inversion in the quiet Sun and other cool stars, yet the viability of that mechanism rests almost solely on the compatibility of empirical H⁻ cooling estimates with the predictions of theoretical acoustic wave production and propagation models (see e.g. Linsky, 1979, and references therein).

Here I intend to clarify the H⁻ cooling controversy by reconsidering a crucial point that has been all but forgotten in the current debate. While H⁻ does cool the chromosphere to some extent, its primary role in the outer atmosphere is that of a strong source of radiative heating. The heating effects are produced by the absorption of photospheric radiation by chromospheric H⁻ ions and are particularly pronounced when departures from LTE are significant. The implications of the H⁻ heating must be considered carefully before one can assess net radiative cooling rates from empirical models.

2. Statistical Equilibrium and Energy Balance in Chromospheric H⁻

A. STATISTICAL EQUILIBRIUM

Here, I briefly summarize the work of Lambert and Pagel (1968), Gebbie and Thomas (1970), and Vernazza et al. (1973, 1976).

The equilibrium concentration of H⁻ ions in the outer atmosphere is established by a balance between a variety of radiative and collisional rates. The most important collisional process is associative detachment by neutral hydrogen atoms,

\[ \text{H}^{-} + \text{H} \rightarrow \text{H}_2 + \text{e}^{-}. \]  

As a result, one must also carefully consider the mechanisms that control the equilibrium concentration of molecular hydrogen (Gebbie and Thomas, 1970).

Vernazza et al. (1973) have expressed the H⁻ portion of the H⁻–H₂ joint statistical equilibrium in a compact form, as follows:

\[ b_{\text{H}^{-}} = \frac{n_{\text{H}^{-}}}{n_{\text{H}^{-}}^{\psi}} = \frac{R^{(0)} + \psi}{R^{(0)}}. \]  

Here the departure coefficient \( b_{\text{H}^{-}} \) is the ratio of the true H⁻ population, \( n_{\text{H}^{-}} \), to that expected in LTE (Vernazza et al., 1976),

\[ n_{\text{H}^{-}}^{\psi} = n_e n_{\text{H}^{-}} \psi_{\text{H}^{-}}(T). \]

In Equation (2),

\[ R^{(0)} = 4\pi \int_0^{\lambda_0} \alpha_\lambda \frac{J^{(0)}_\lambda}{(hc/\lambda)} d\lambda \]  

© Kluwer Academic Publishers • Provided by the NASA Astrophysics Data System
is the photodetachment rate coefficient at the stellar surface,

\[ R^+ = 4\pi \int_0^{\lambda_0} \alpha_\lambda \frac{B_\lambda(T)}{(hc/\lambda)} \, d\lambda \]  

(5)

is the radiative recombination rate per \( \text{H}^- \) ion present in LTE, and \( \mathcal{C} \) is an expression containing the several important dissociation rates corresponding to the principal reaction channels that form and destroy \( \text{H}^- \) ions and \( \text{H}_2 \) molecules (Vernazza et al., 1973). (Stimulated recombinations are treated in LTE in Equation (5), for simplicity.)

It is straightforward to evaluate the radiative and collisional coefficients given an empirical model that specifies temperatures and densities as a function of height in the solar atmosphere.

B. ENERGY BALANCE IN \( \text{H}^- \)

Although the reactions that control the equilibrium concentrations of \( \text{H}^- \) and \( \text{H}_2 \) are several, the overall energy balance of the \( \text{H}^- - \text{H}_2 \) system is quite simple. According to Gebbie and Thomas, the net energy balance can be written as

\[ \Delta e = n_{\text{H}^-}^*(\varepsilon^+(T) - b_{\text{H}^-} \varepsilon^{(0)}) \text{ ergs cm}^{-3} \text{ s}^{-1}, \]  

(6)

where

\[ \varepsilon^{(0)} = 4\pi \int_0^{\lambda_0} \alpha_\lambda J^{(0)}_\lambda \, d\lambda \]  

(7)

is the rate coefficient for the energy extracted from the background radiation field by photodetachments, while

\[ \varepsilon^+ = 4\pi \int_0^{\lambda_0} \alpha_\lambda B_\lambda(T) \, d\lambda \]  

(8)

represents the energy returned to the radiation field by radiative recombinations.

Physically, the cooling (\( \Delta e > 0 \)) or heating (\( \Delta e < 0 \)) of the plasma occurs only by a net exchange of energy between the radiation field and the internal energy reservoirs (kinetic and potential) of the gas. Pure collisional processes cannot heat or cool the gas directly, but merely convert kinetic energy into potential energy, and vice versa. (Nevertheless, collisions play a central role in establishing the equilibrium concentration of \( \text{H}^- \) ions, which in turn controls the amount of energy absorbed from the photospheric radiation field.)

C. HEATING AND COOLING RATES IN AN EMPIRICAL SOLAR MODEL

Table I lists atmospheric parameters for an empirical model of the solar temperature minimum region (Vernazza et al., 1976; Avrett, 1977). Also included are derived
Table I
Atmospheric parameters and derived quantities

\[ R^{(0)} = 1.14 \times 10^6 \text{ s}^{-1}; \quad \varepsilon^{(0)} = 3.01 \times 10^{-6} \text{ ergs s}^{-1} \]

<table>
<thead>
<tr>
<th>Height (km above ( \tau_{5000} = 1 ))</th>
<th>( m \times 10^{-2} ) (g cm(^{-2}))</th>
<th>( T ) (K)</th>
<th>( n_e \times 10^{10} ) (cm(^{-3}))</th>
<th>( n_H \times 10^{14} ) (cm(^{-3}))</th>
<th>( b_{H^-} )</th>
<th>( b_{H_2} )</th>
<th>( \phi_R(T) ) (10(^{-27}) ergs ( \text{cm}^3 \text{s}^{-1} ))</th>
<th>( \phi_{SE}(T) ) (10(^{-27}) ergs ( \text{cm}^3 \text{s}^{-1} ))</th>
<th>( T_{crit} ) (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1575</td>
<td>0.003</td>
<td>6529</td>
<td>2.4</td>
<td>0.009</td>
<td>3.36</td>
<td>3.00</td>
<td>8.3</td>
<td>0.67</td>
<td>5450</td>
</tr>
<tr>
<td>1375</td>
<td>0.009</td>
<td>6400</td>
<td>1.5</td>
<td>0.03</td>
<td>3.15</td>
<td>2.20</td>
<td>8.2</td>
<td>0.60</td>
<td>5440</td>
</tr>
<tr>
<td>1200</td>
<td>0.03</td>
<td>6200</td>
<td>2.2</td>
<td>0.08</td>
<td>2.82</td>
<td>1.70</td>
<td>7.9</td>
<td>0.50</td>
<td>5410</td>
</tr>
<tr>
<td>1140</td>
<td>0.04</td>
<td>6140</td>
<td>2.7</td>
<td>0.12</td>
<td>2.71</td>
<td>1.59</td>
<td>7.8</td>
<td>0.49</td>
<td>5390</td>
</tr>
<tr>
<td>1075</td>
<td>0.06</td>
<td>6040</td>
<td>3.3</td>
<td>0.19</td>
<td>2.55</td>
<td>1.46</td>
<td>7.7</td>
<td>0.46</td>
<td>5350</td>
</tr>
<tr>
<td>975</td>
<td>0.12</td>
<td>5910</td>
<td>4.5</td>
<td>0.38</td>
<td>2.33</td>
<td>1.30</td>
<td>7.5</td>
<td>0.49</td>
<td>5250</td>
</tr>
<tr>
<td>900</td>
<td>0.21</td>
<td>5720</td>
<td>4.9</td>
<td>0.67</td>
<td>2.03</td>
<td>1.17</td>
<td>7.3</td>
<td>0.52</td>
<td>5130</td>
</tr>
<tr>
<td>850</td>
<td>0.31</td>
<td>5580</td>
<td>5.0</td>
<td>0.99</td>
<td>1.82</td>
<td>1.10</td>
<td>7.1</td>
<td>0.55</td>
<td>5040</td>
</tr>
<tr>
<td>800</td>
<td>0.39</td>
<td>5360</td>
<td>10.0</td>
<td>1.3</td>
<td>1.57</td>
<td>1.11</td>
<td>6.8</td>
<td>0.41</td>
<td>5000</td>
</tr>
<tr>
<td>750</td>
<td>0.58</td>
<td>5150</td>
<td>8.4</td>
<td>2.0</td>
<td>1.34</td>
<td>1.04</td>
<td>6.6</td>
<td>0.36</td>
<td>4920</td>
</tr>
<tr>
<td>700</td>
<td>0.88</td>
<td>4890</td>
<td>7.3</td>
<td>3.3</td>
<td>1.13</td>
<td>1.01</td>
<td>6.2</td>
<td>0.08</td>
<td>4860</td>
</tr>
<tr>
<td>650</td>
<td>1.4</td>
<td>4600</td>
<td>7.7</td>
<td>5.3</td>
<td>0.970</td>
<td>0.998</td>
<td>5.9</td>
<td>-0.64</td>
<td>4820</td>
</tr>
<tr>
<td>600</td>
<td>2.2</td>
<td>4350</td>
<td>11</td>
<td>9.0</td>
<td>0.903</td>
<td>0.995</td>
<td>5.6</td>
<td>-1.8</td>
<td>4790</td>
</tr>
<tr>
<td>550</td>
<td>3.5</td>
<td>4170</td>
<td>15</td>
<td>15</td>
<td>0.899</td>
<td>0.995</td>
<td>5.3</td>
<td>-3.2</td>
<td>4770</td>
</tr>
<tr>
<td>525</td>
<td>4.5</td>
<td>4150</td>
<td>18</td>
<td>20</td>
<td>0.914</td>
<td>0.996</td>
<td>5.3</td>
<td>-3.5</td>
<td>4770</td>
</tr>
<tr>
<td>500</td>
<td>5.8</td>
<td>4150</td>
<td>23</td>
<td>25</td>
<td>0.930</td>
<td>0.997</td>
<td>5.3</td>
<td>-3.7</td>
<td>4760</td>
</tr>
<tr>
<td>450</td>
<td>9.6</td>
<td>4200</td>
<td>35</td>
<td>41</td>
<td>0.958</td>
<td>0.998</td>
<td>5.4</td>
<td>-3.5</td>
<td>4760</td>
</tr>
<tr>
<td>400</td>
<td>16</td>
<td>4300</td>
<td>58</td>
<td>65</td>
<td>0.977</td>
<td>0.999</td>
<td>5.5</td>
<td>-2.8</td>
<td>4750</td>
</tr>
<tr>
<td>350</td>
<td>25</td>
<td>4460</td>
<td>93</td>
<td>100</td>
<td>0.991</td>
<td>1.000</td>
<td>5.7</td>
<td>-1.7</td>
<td>4750</td>
</tr>
<tr>
<td>300</td>
<td>40</td>
<td>4600</td>
<td>150</td>
<td>160</td>
<td>0.998</td>
<td>1.000</td>
<td>5.9</td>
<td>-0.83</td>
<td>4750</td>
</tr>
</tbody>
</table>

\( a \) Vernazza et al. (1976), and Avrett (1977).

\( b \) + = cooling; − = heating.

Departure coefficients, \( b_{H^-} \) and \( b_{H_2} \), and the energy balance parameter \( \Delta e \). I have expressed \( \Delta e \) in the form of a standard radiative cooling curve (e.g. Cox and Tucker, 1969),

\[ \phi_{SE}(T) = \frac{\Delta e}{n_e n_H} \text{ ergs cm}^3 \text{s}^{-1}. \]  

(9)

Here, the subscript refers to the statistical equilibrium solution for the \( H^- \) population and cooling rate.

I determined the fixed photodetachment rate \( R^{(0)} \), and the corresponding energy absorption coefficient \( \varepsilon^{(0)} \), by numerical integrations of Equations (4) and (7), respectively. In these integrations, I adopted an \( H^- \) photodetachment cross section \( \alpha_\lambda \) based on the multichannel \( j \)-matrix formalism of Broad and Reinhardt (1976). I estimated the surface monochromatic mean intensity field \( J^{(0)}_\lambda \) empirically, using an average solar irradiance spectrum \( \mathcal{F}_\lambda \) taken from Pierce and Allen (1977), and 'Eddington factors',

\[ f_\lambda = J^{(0)}_\lambda / \mathcal{F}_\lambda, \]  

(10)
derived from the polynomial representations of near ultraviolet, optical and infrared continuum limb darkening curves tabulated by Pierce and Slaughter (1977) and by Pierce et al. (1977). The calculated Eddington flux factors are a slowly varying function of wavelength. For example, \( f_\lambda \) increases from about 0.12 at 0.3 \( \mu \)m to about 0.15 at the \( H^- \) bound-free edge near 1.6 \( \mu \)m. (In the limit of constant center-to-limb behavior, \( f_\lambda = (2\pi)^{-1} \approx 0.16. \))

The estimated empirical solar photodetachment rate and energy absorption coefficient are included in Table I.

I determined the radiative recombination rate \( R^+(T) \) and the energy emission coefficient \( \epsilon^+(T) \) by numerical integrations of Equations (5) and (8), respectively.

Finally, I adopted the dissociation rate coefficients for \( H^- \) and \( H_2 \) summarized by Vernazza et al. (1973).

### 3. Implications

The derived values of \( g_{SE} \) given in Table I imply that \( H^- \) is a significant source of heating over a wide range of temperatures in the upper photosphere and low chromosphere.

In the high density layers below \( T_{\text{min}} \) where \( b_{H^-} \equiv 1 \) owing to the large collision rates, \( H^- \) is a net source of heating for temperatures lower than a critical temperature \( T_{\text{crit}} \), where

\[
\epsilon^+(T_{\text{crit}}) = \epsilon^{(0)},
\]

or

\[
T_{\text{crit}} \approx 4740 \text{ K}.
\]

In the low density layers above \( T_{\text{min}} \) where the photospheric radiation field largely controls departures from LTE in \( H^- \), the critical temperature rises to the color temperature of the background radiation, namely

\[
\frac{\epsilon^+(T_{\text{crit}})}{R^+(T_{\text{crit}})} = \frac{\epsilon^{(0)}}{R^{(0)}},
\]

or

\[
T_{\text{crit}} \approx 5450 \text{ K}.
\]

In the first situation, which corresponds to LTE, a radiative equilibrium boundary temperature \( T^{(0)} \) well below \( T_{\text{crit}} \) can be established by LTE line blanketing (Kurucz, 1974). The second situation, namely statistical equilibrium in \( H^- \) (and the lines), presents us with a considerably different picture than the first. Here, we must recognize that the strong surface cooling by opaque line cores in LTE-RE can be decreased significantly by the scattering terms that appear in statistical equilibrium.

* This is not strictly LTE, since \( J_s \neq B_\lambda \), but conforms to the central assumption used in LTE-RE simulations, namely that all of the atomic populations are given by the LTE values.
In fact, some kinds of lines may become net heating sources themselves, owing to population imbalances driven, for example, by photoionizations. Furthermore, H$^-$ can be a net source of heating over a wider range of temperatures than in the LTE case. To illustrate the latter effect, I have included in Table I the critical temperatures $T_{\text{crit}}$ at which energy balance in H$^-$ is attained for the particular density stratification of the VAL model. The critical temperature would be essentially the local radiative-statistical equilibrium temperature if H$^-$ were the most important opacity source in the outer atmosphere. The significant ‘nebular’ temperature rise at low densities is apparent (Cayrel, 1963; Gebbie and Thomas, 1970).

It is clear that radiative equilibrium under the constraint of statistical equilibrium is attained by a balance between many complex and competing energy terms. There is no guarantee that the RE temperature structure in the highly nonLTE situation will bear any resemblance to, for example, the LTE line-blanketed solar model proposed by Kurucz (1974). As Praderie and Thomas correctly point out, the nebular effects in H$^-$ may well be sufficient to force a Cayrel-type temperature inversion without substantial mechanical heating. In short, the initial portion of the chromospheric temperature rise could be simply a consequence of radiative-statistical equilibrium (RSE).

Ulmschneider has recognized this potential problem in his work. In particular the elaborate RE solar models constructed by Kurucz and others are typically hotter than conventional empirical models in the neighborhood of $T_{\text{min}}$. Ulmschneider and collaborators have therefore adopted $T_{\text{min}}$ in the empirical model as an approximation to the true RSE boundary temperature $T^{(0)}$. They argue that $T_{\text{min}}$ is at worst an upper limit to $T^{(0)}$, owing to the likely presence of significant mechanical heating at the base of the chromosphere. However, we have seen above that the actual RSE thermal structure could include a significant temperature rise in the low density outer layers, even without any mechanical heating. In short, there is no guarantee that $T_{\text{min}} \approx 4200$ K is in fact an upper limit to the true RSE boundary temperature.

Suppose, for example, that the actual $T^{(0)}$ is somewhat hotter than the empirical $T_{\text{min}}$. What effects might we expect, given Ulmschneider’s prescription for estimating excess radiative losses in H$^-$?

First, there would be little change in the temperature-dependent component of the excess radiative loss rate. In particular, Ulmschneider’s cooling prescription is based on the differential recombination rate,

$$
\Delta \phi_R(T, T^{(0)}) = \phi_R(T) - \phi_R(T^{(0)}),
$$

where $\phi_R(T) = n_{\text{H}}^* e^\dagger(T)/n_e n_{\text{H}}$ is the density independent coefficient of the recombination cooling. I have tabulated $\phi_R(T)$ for the VAL model temperatures in Table I. Because $\phi_R(T)$ is a slowly varying function of temperature, $\Delta \phi$ is relatively insensitive to the choice of $T^{(0)}$. For example, $\Delta \phi_R(6000, T_{\text{min}}) \approx 2.4 \times 10^{-27}$ ergs cm$^3$ s$^{-1}$, while $\Delta \phi_R(6000, 4600) \approx 1.8 \times 10^{-27}$ is only somewhat smaller. Kalkofen and Ulmschneider argue that the differential prescription tends to cancel the H$^-$ heating terms to first order, if $T^{(0)}$ is known reliably.
Second, what does change significantly with changing $T^{(0)}$ is the thickness of the chromosphere in mass column density, $m_{\text{chrom}}(\text{g cm}^{-2})$. The total chromospheric excess radiative losses are very sensitive to this quantity though the integral of the local net cooling $\Delta e$ over height,

$$e_{\text{tot}} = \int_{m_{\text{chrom}}}^{m_{\text{chrom}} - 1} \Delta \phi(T) n_e n_H \, dz$$

$$= \int_{m_{\text{chrom}}}^{m_{\text{chrom}} - 1} \Delta \phi \frac{n_e n_H}{\rho} \, dm$$

$$\approx (1.4 m_H)^{-1} \Delta \phi \bar{n}_e m_{\text{chrom}}.$$  \hspace{1cm} (14)

Here, the bars represent chromospheric averages, and $\rho \equiv 1.4 m_H n_H$ is the material density (g cm$^{-3}$) for a 10% helium abundance (by number). The averages of $\Delta \phi$ and $n_e$ are justified because both of these quantities are relatively slowly varying functions of height in the chromosphere (at least when one uses the LTE $\Delta \phi$ given by Equation (13)).

Ulmschneider essentially defines the thickness of the chromosphere as the depth at which the empirical temperature $T$ equals the RSE boundary temperature. If $T^{(0)} = T_{\text{min}}$, then $m_{\text{chrom}} = m_{T_{\text{min}}} \approx 5 \times 10^{-2}$ g cm$^{-2}$ (for the VAL model). However, if the true ‘boundary’ temperature is in fact higher than $T_{\text{min}}$, then $m_{\text{chrom}}$ will be smaller than $m_{T_{\text{min}}}$. For example, $m_{\text{chrom}}[T^{(0)} = 4600 \text{ K}] \approx 1 \times 10^{-2}$. In the first case, the total cooling $e_{\text{tot}} \approx 3 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ is considerably larger than in the second case, $e_{\text{tot}} \approx 4 \times 10^5$ [for $\bar{n}_e \approx 5 \times 10^{10}$ cm$^{-3}$, and $\Delta \phi \approx \Delta \phi_R (6000, T^{(0)})$.

The large decrease in $e_{\text{tot}}$ with a small increase in $T^{(0)}$ is further amplified if one uses the net differential cooling rate in statistical equilibrium,

$$\Delta \phi_{\text{SE}}(T, T^{(0)}) = \phi_{\text{SE}}(T) - \phi_{\text{SE}}(T^{(0)}),$$  \hspace{1cm} (15)

instead of the LTE differential recombination cooling curve. The statistical equilibrium $\Delta \phi$ is appropriate for assessing differential cooling between empirical and RSE models. In fact, this is essentially the case considered by Kalkofen and Ulmschneider, although they steadfastly maintained that $T^{(0)} \approx T_{\text{min}}$. Their assumption has important implications, because $\Delta \phi_{\text{SE}}(6000, T_{\text{min}}) \approx 4 \times 10^{-27}$ ergs cm$^3$ s$^{-1}$ is very similar to the differential recombination result cited above. Consequently, Kalkofen and Ulmschneider conclude that nonLTE effects are not particularly significant, because the total cooling obtained from $\Delta \phi_{\text{SE}}$ with $T^{(0)} = T_{\text{min}}$, namely $e_{\text{tot}} \approx 4 \times 10^6$ ergs cm$^{-2}$ s$^{-1}$ for the atmospheric parameters given above, is not very much different from the LTE case (see above). Unlike the LTE situation, however, $\Delta \phi_{\text{SE}}$ is a sensitive function of $T^{(0)}$. For example, if $T^{(0)}$ is increased to 4600 K, then $\Delta \phi_{\text{SE}}$ decreases a factor of four to $\approx 1 \times 10^{-27}$. Consequently, the decreases in $m_{\text{chrom}}$ and $\Delta \phi_{\text{SE}}$ conspire to drop $e_{\text{tot}} \approx 2 \times 10^5$ a factor of twenty from the case with $T^{(0)} \approx T_{\text{min}}$ to that with $T^{(0)} \approx 4600$ K.
4. Discussion

The energy balance of the low chromosphere is of fundamental importance for understanding the reasons why the outer atmospheres of cool stars exhibit decidedly nonclassical temperature inversions. Ulmschneider's comparison of theoretical acoustic flux models with empirical estimates of chromospheric radiative cooling, in an effort to identify the mechanical heating mechanism, is certainly a step in the right direction. Nevertheless, before we can realistically apply Ulmschneider's excess radiative loss prescription, we must solve two subsidiary problems.

First, we must determine the appropriate temperature-pressure stratification of the solar outer atmosphere within the combined constraints of radiative and statistical equilibrium. In this regard, Athay's (1970) study should serve as a prototype, although as Praderie and Thomas argue, Athay did not include all of the potential non-LTE heating and cooling effects in the line cores in a self-consistent way. Nevertheless, a detailed RSE simulation should be well within the capabilities of present day computing techniques.

Second, we must identify all of the important sources of radiative cooling for temperatures below about 6000 K. In particular, the bulk of the chromospheric radiative losses likely occurs near the base of the temperature inversion where the gas pressures are largest. The fact that conventional empirical models, such as the VAL, tend to have lower temperatures in the upper photosphere than predicted by the LTE-RE models, strongly suggests the presence of additional coolants that were not considered in the LTE, atomic line-blanketed simulations, for example the extensive infrared vibration-rotation bands of abundant molecules such as carbon monoxide. Those cooling mechanisms that are effective at low temperatures on the photospheric side of the chromospheric temperature inversion, are also likely to be important at low temperatures on the chromospheric side. The collective cooling curve for \( T < 6000 \text{ K} \) in the chromosphere must be established carefully before differential radiative losses can be assessed reliably from comparisons of empirical and RSE models.

5. Conclusions

I find that a major criticism by Praderie and Thomas of Ulmschneider's chromospheric radiative loss estimates is indeed legitimate. Namely, the specification of the true radiative-statistical equilibrium boundary temperature of the photosphere is of critical importance in deriving differential cooling rates from empirical chromospheric models. As Praderie and Thomas have argued, the RSE temperature plays an important role in determining the thermal coefficient of the net differential cooling function. I add to their argument that \( T^{(0)} \) plays an equally important role in establishing the physical thickness of what is considered to be truly 'chromospheric' material. In short, Ulmschneider's radiative loss prescription, which is based on the assumptions that \( T_{\min}^{\text{empirical}} \geq T^{(0)} \) and that \( T_{\min}^{\text{empirical}} \) defines the 'thickness' of the
chromosphere, does not have a rigorous foundation. Therefore, Ulmschneider’s contention that acoustic wave dissipation is the only viable heating mechanism to power the ‘large’ empirical chromospheric cooling rates has not been proved conclusively, especially since the radiative losses derived by his prescription can be overestimated by an order of magnitude.

Acknowledgements

This work was supported by the National Aeronautics and Space Administration under grant NGL-06-003-057 to the University of Colorado. I thank J. L. Linsky and K. B. Gebbie for their comments, and the National Center for Atmospheric Research for providing computing time. In carrying out this work, I have benefited from participation in the Skylab Workshop on Active Regions, which was sponsored by NASA and NSF through NCAR/HAO.

References