Observational and Interpretational Challenges

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Abstract.

I re-visit the question: how can we use spectra to extract meaningful information on the thermodynamics of solar and stellar coronae? Earlier work has shown that full emission-line inversions are ill-posed, non-unique and intractable, and that diagnostic line-ratio techniques are a subset of inverse methods whose validity depends on the homogeneity of the emitting plasma. Simple inhomogeneous models reveal systematic problems with line-ratio diagnostic techniques whose magnitude increases with the degree of inhomogeneity. Furthermore, because different plasma configurations lead to very similar spectra, such techniques cannot be used to prove or falsify anything but the simplest hypotheses concerning the plasma structure. The reliability of line-ratio diagnostic techniques thus hinges on the answer to the central question: how inhomogeneous are coronae? To answer this question we must examine physical models, because current observations cannot resolve the smallest scales of plasma inhomogeneity. Our incomplete knowledge of the physics of the coupled chromosphere-corona system – especially of the energy equation – suggests that although field aligned heat conduction can serve as an effective thermostat, there is no mechanism that can produce constant pressure configurations across adjacent field lines. Coronae may thus be inhomogeneous on all scales perhaps down to ion gyro-radii, and serious and systematic errors should be expected when commonly used spectral diagnostic techniques are applied. The safest approach appears to lie in forward modeling.

1. Introduction

Stellar coronae present us with very challenging problems. Coronae are complex, nonlinear physical systems that are driven by the turbulent atmosphere and convection zone beneath primarily through electrodynamic processes (e.g. Narian & Ulmschneider 1990). Coronae probably relax non-linearly to states that naturally involve discontinuities (Parker 1994). It is therefore not surprising that coronal heating remains as big a problem in the 21\(^{st}\) century as it was in the 20\(^{th}\). It will be many years before we can fly particle detectors and magnetome-

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ters through the solar corona to measure directly quantities of interest, and we may never be able to fly instruments close enough to low-lying regions of most interest. We are therefore left with no option but to interpret the photons that are emitted or absorbed by coronal plasma, in our quest for the solution to the heating problem, the "Holy Grail" of coronal physics.

For more than 6 decades, many researchers have refined techniques to try to understand what the photons can tell us about astrophysical plasmas. Photon spectra, through radiative transfer, reflect spatially integrated plasma properties. Coronal EUV or X-ray emission from coronae is generally optically thin, and photospheres are essentially black, so we measure an integral down to the photosphere (or space if observing above the limb) of all plasma emission along the line-of-sight. These special conditions have led to the development of tools for estimating thermal properties of the emitting plasma, such as electron temperature \( T \) and density \( n \). Such measurements are needed for quantitative studies of heating mechanisms because \( T \) and \( n \) determine the magnitude or source and sink terms in the plasma energy equation. These tools are the subject of this review, my specific aim being review and assess the reliability of methods that are commonly used to diagnose the temperatures and pressures of coronal plasmas, which often form the starting points of more detailed analyses (e.g., Aschwanden et al. 2000).

2. Overview of approaches

Three approaches are commonly used to analyze optically thin emission lines: inverse methods (differential emission measure analysis), line ratio methods, and forward approaches (see Figure 1). All three approaches are highlighted below. They all involve physical models, at least at the atomic level, and all are ill-posed in the sense that different plasma configurations can yield the same observed data. The interpretation of emission lines is in general non-unique, so that to find a particular solution (or family of solutions), one is obliged to add more information. A critical question is then: how should we add this information? To answer this we need to look at the problem more closely.

The frequency-integrated emergent intensity contributed by an optically thin emission line labeled \( i \) along a path length \( Z \) is

\[
I_i = \frac{h \nu_i}{4\pi} \int_Z n_i(z, t) A_i \, dz .
\]  

(1)

where \( \nu_i \) is the central frequency of the transition, \( n_i(z, t) \) is the population density of the upper level of transition \( i \), and \( A_i \) is the Einstein A-coefficient of the transition. Under standard "coronal" conditions (these are reviewed by, e.g., Mason & Monsignori-Fossi 1994) the populations \( n_i(z, t) \) become functions of electron density \( n \) and temperature \( T \), and then we can write

\[
I_i = \int \int K_i(T, n) \mu(T, n) \, dT \, dn ,
\]

(2)

and where \( \mu(T, n) \) is the source term, the emission measure differential in temperature and density. All information on abundances and atomic cross sections...
is implicit in the kernels \( K_i(T, n) \). When the kernels all depend roughly on \( n \) as \( n^2 \) (this is the case for most permitted transitions), \( K_i(T, n) = n^2 G_i(T) \) and equation (2) is integrated over \( n \) to give

\[
I_i = \int G_i(T) \xi(T) \, dT ,
\]

where this equation defines \( \xi(T) \), the standard "differential emission measure".

In the forward approach, information is explicitly added through the physical ingredients included in the model, and boundary conditions, from which \( n(z, t) \) are computed directly and inserted into equation (1) (or its frequency-dependent counterpart). Direct comparisons of observed and computed data are made. The inverse approach seeks solutions \( \mu(T, n) \) or \( \xi(T) \) to equations (2) and (3). This is a very different proposition from the forward approach. Information is added via assumptions of two kinds. First it is added implicitly by simply casting the problem into this form: for example we must assume \( K_i \) depends functionally only on \( T \) and \( n \), which may or may not be true. Secondly, because we must formally "invert" integrals, we must add necessary mathematical "smoothness" constraints to the desired solution to obtain any meaningful family of solutions at all (Craig & Brown 1986). The distribution functions \( \mu(T, n) \) or \( \xi(T) \) that are sought contain the most information on \( T \) and \( n \) that in principle can be obtained from the emission lines, given the required assumptions. In the "line-ratio" approach, yet more assumptions are needed without which no meaningful answer can be determined. These originate from application of "Occam's Razor", the principle which says one should take the simplest solution that is compatible with the data. To estimate \( T \) using temperature-sensitive line-ratios, one approximates \( \xi(T) \) by a Dirac \( \delta \)-function and solves for the temperature \( T_{ij} \) which yields the observed ratio of intensities \( I_i/I_j \) through equation (3). The approach thus seeks some "representative" value of \( T \) (or, with other assumptions, \( n \)) of the plasma. The approach, the earliest example of which may be Menzel et al. (1941), is therefore a restricted version of the inverse approach (McIntosh et al. 1998, Judge & McIntosh 2000). By replacing the intensity integrals by "one-point quadratures", it is seen to have something of the flavor of the well-known Eddington-Barbier relationship.

The healthy (if somewhat strongly-felt) debate at this and other meetings concerns the choice of methods by which data are analyzed. The heart of this debate clearly amounts to how we choose to add information needed to interpret the spectra in terms of thermal plasma properties. The power of Occam's Razor is not to be denied, and the line-ratio approach certainly dominates the literature. But we should remember that coronae are not simple physical systems, and that the inversions are very ill-posed. This combination makes me ill at ease. The line ratio and inversion methods may appear to represent a straightforward and common-sense application of Occam's Razor, but we must recognize that the drastic assumptions needed in these methods may cut a lot deeper than we had hoped, deep enough in fact to cut out the very essence of the physical processes we are looking for. Thus my personal choice is to draw on forward models to add information instead of the drastic assumptions required in line-ratio or even inverse techniques (e.g. Wikstel et al. 1998). Faced with the unreasonable situation in which we might argue this point ad nauseam, I prefer to ask what should we do to make the best use of data obtained at great expense. Several
options present themselves. We might (1) recognize but then sweep the problem under the carpet (with Occam’s Broom perhaps?), and continue with inverse and Occam’s Razor approaches, because until forward models become standard practice, we believe that these methods are the best we have (Laming 1998), or (2) investigate physical properties of the plasmas influencing the interpretation of the lines, and study the success or failure of various techniques, or even (3) “forget the whole thing and do something more profitable like hang gliding” (actually suggested by Craig & Brown 1986)! In the rest of this paper I follow point 2, in spite of the appeal of 3.

3. Coronal physics: does it support simple spectroscopic diagnosis?

The physical complexity of the corona renders a general attack on this question open to criticism, because one can all too easily find physical models in which standard spectroscopic techniques will fail badly to reproduce properties of the model. I therefore shall attempt to answer a simpler question: What is the likelihood that inverse and line-ratio approaches will succeed?
Figure 2. Thermal structure of two 1D atmospheres (left panel) placed side-by-side (right panel), derived from semi-empirical models. The downward conductive flux from the corona differs by a factor of 10. The details of the models do not matter. They were based upon model C of Vernazza et al. (1981) and the plage model of Avrett (1981), but with the thermal structure above $10^4$ K determined using typical emission measure distributions and the formalism outlined by Jordan (1992). Each of these atmospheres is in essence a "mini-atmosphere" of RTV.

3.1. Some simple examples

I take a step-by-step approach, beginning with the simplest structure that might reasonably be observed in the corona: a static, hydrostatically stratified, horizontally homogeneous structure whose thermal structure is controlled by the balance of steady heating, radiation and heat conduction. I will call such an atmosphere a "building block" of the corona, in the sense implied by Rosner et al. (1978) (henceforth "RTV"). The X-ray corona appears to be made up of a collection of "mini-atmospheres" or "building blocks" that are thermally insulated from each other by inefficient cross-field heat conduction. Each building block is homogeneous in the sense that it has a one-to-one mapping of plasma temperature to density represented by a constant-area locus in the $(T-n)$ plane. Two "building blocks" are shown in Figure 2. Judge & McIntosh (2000) computed the spectra of building blocks and applied inverse and line-ratio techniques to try to see if the model's structure could be recovered, assuming reasonable values for uncertainties in atomic parameters (Judge et al. 1997). The inverse problem (solving for $\mu(T, n)$ from a set of $I_i$ using equation 2) is so badly posed
as to be impossible, practically speaking. This is a general result that depends only on the kernel properties $K_i(T, n)$ (Judge et al. 1997, their section 3). The inversions for $\xi(T)$ are more tractable but require mathematical "smoothness" or other non-physical constraints to get a meaningful solution at all (e.g. Craig & Brown 1976). For the simplest case of just one building block, the line-ratio technique revealed the correct locus of points in the $(T, n)$ plane, provided one uses the additional assumption that each ion radiates at its temperature of peak equilibrium ionization fraction (see Figure 3 of Judge & McIntosh 2000).

The situation changes when inhomogeneity is introduced, as shown by Figure 3 of Judge & McIntosh (2000) where just two "building blocks" contribute to the emission. As expected, the line-ratio techniques begin to fail, yielding mean values of the density that depend not on the plasma per se but also on the particular density sensitive line pair considered. What is not perhaps expected, is the confusing patterns of points in the $(T, n)$ plane that obviously depend on the line pairs used, and the fact that the analysis fails to confirm or falsify the hypothesis that any plasma exists under constant pressure conditions. Yet, this is arguably the simplest possible departure from homogeneous structure in a corona, and it may be a reasonable approximation for a star with quiet and active regions on the visible hemisphere. Thus, the question posed in this section is translated to: how likely is it that a given line-of-sight intercepts just one building block? That is a very good question that I will speculate on below, noting here that the answer requires knowledge of very uncertain physical processes in the energy equation. Unfortunately this means, in principle, that we have to know the answer to the heating problem before we have started!

A qualitatively different case was studied by Judge (2000), who started from the inverse approach and systematically increased the density inhomogeneity from a Dirac $\delta$-function to Gaussian distributions in isothermal plasmas. Line-ratio methods systematically underestimate physical filling factors (Almeaky et al. 1989). The systematic error increases monotonically with the width of the Gaussian distributions.

I conclude that inversions are intractable and often rely on mathematical (not physical) constraints. The line-ratio methods give you an answer, which is correct if the plasma really is homogeneous. The catch is that the data cannot tell you that, some other prior knowledge is required. Worse still the answer you get is in fact determined by the assumptions and not the data, it is therefore generally subjective. Under inhomogeneous conditions the answers also contain systematic errors. The viability of line-ratio spectroscopic techniques depends on the answer to the following critical question: how homogeneous is the emitting plasma? I now investigate what reasons might be found to support the notion that coronae are relatively homogeneous, even on the $\approx 1$ Mm scales at which the solar corona has been spatially resolved (the solar radius is 700 Mm).

3.2. How homogeneous is the solar corona?

This is a difficult question to answer. While theory (below) suggests that the corona is extremely inhomogeneous on all scales observed thus far, observations (section 3.2.) present us with something of a conundrum: the corona appears to be highly organized on large scales but finely structured on small scales.
Preliminary speculations  Coronal inhomogeneities are expected in both space and time. Spatial inhomogeneities are expected to be strongest across magnetic field lines, because parallel heat conduction is very efficient, and pressure equilibration occurs rapidly (typical footpoint-footpoint sound crossing times are 200s for active region loops). By comparison, classical heat conduction across field lines is very inefficient at coronal temperatures, and no other efficient cross-field heat transport mechanisms have been found (section 3.2.). “Temporal inhomogeneities” (i.e. dynamic evolution of plasma) are expected when rapid heating or cooling occurs, as might be expected if the corona is heated by “nanoflares” (Parker 1988) or strongly time-dependent wave heating (e.g. Ofman et al. 1998).

The corona is of course part of a larger system, a point whose implications are not always fully appreciated. Models that include the mass reservoir at the coronal base allow quite different solutions from those that treat the corona as a separate structure. For example, well-known loop “scaling laws” (section 3.2.) rely implicitly on coupling to the chromosphere to allow evolution to pressure and energy balance (RTV), and chromospheric coupling naturally explains otherwise puzzling fundamental properties of the fast solar wind mass flux (Holzer et al. 1997). It may also be that the lower atmospheric layers somehow avoid the “cross-field heat transport” problem (section 3.2.). In terms of dynamics, Athay (2000) has suggested that, under conditions where neutral and charged particles are heated at different rates, the upper chromosphere can become unstable to thermal perturbations. Subsequently, the upper chromosphere and corona would undergo a continual evolution which may also lead to spicules, and render coronal physics inextricably and dynamically dependent on chromospheric physics. Some detrimental affects of dynamics on plasma diagnostic techniques are discussed by Wikstøl et al. (1998), among others.

None of the above speculations supports the idea that coronae are spatially or temporally homogeneous on observable scales. But let us look a little closer.

Clues from 1D calculations  1D loop models (the “building blocks” discussed above) contain some important physics that can shed light on the expected 3D thermal structure of the corona, in the following sense. The solutions obtained by RTV (and more general forms given by Jordan 1992 which give different constants of proportionality) yield expressions for the characteristic peak temperature \( \langle T \rangle \), pressure \( \langle P \rangle \) and X-ray intensity \( I_X \) in terms of the loop length \( \mathcal{L} \) and the base energy flux \( \mathcal{F} \) erg cm\(^{-2}\) s\(^{-1}\) which is assumed to be dissipated entirely in the corona. These “scaling laws” depend largely on well understood physics (field-aligned heat conduction) in the energy equation, and should be quite robust:

\[
\langle T \rangle \propto (\mathcal{F} \cdot \mathcal{L})^{2/7} \tag{4}
\]

\[
\langle P \rangle \propto \left( \frac{\mathcal{F}^6}{\mathcal{L}} \right)^{1/7} \tag{5}
\]

\[
I_X \propto \xi(T_M) = \frac{P^2 \cdot \mathcal{L}}{T} \propto \left( \frac{\mathcal{F}^{10}}{\mathcal{L}^3} \right)^{1/7}, \tag{6}
\]

leading to the more familiar “loop scaling laws” \( \langle P \rangle \propto \langle T \rangle^{3/\mathcal{L}} \) and \( F_X \propto \langle T \rangle^{5/\mathcal{L}} \). Equation (4) says that the corona is an effective thermostat: loops of a given
length $\mathcal{L}$ but with different values of $\mathcal{F}$ will have similar temperatures. However, equation (5) says that they will have quite different pressures. Several adjacent building blocks should, if $\mathcal{F}$ varies between them, contain almost isothermal plasma but with a wide variety of densities.

It is important to specify the loop thermal parameters in terms of $\mathcal{L}$ and $\mathcal{F}$ because these parameters are determined to at least some degree by the forcing of higher energy density plasma at photospheric or chromospheric heights. Note that because $\mathcal{F}$ is assumed to be dissipated entirely in the corona, the formalism implicitly includes a strong statement concerning $\text{div} \mathcal{F}$ along the loop. For example, if there is no dissipation, the magnetic free energy flows out of the other footpoint or is stored $\textit{in situ}$ for later release. Thus $\mathcal{F}$ as specified in the RTV formalism must depend not only on the mechanical flux, but also on the dissipation, i.e. on the coronal conditions themselves.

Jordan (1992) has generalized the scaling laws to include different relative magnitudes of terms in the energy equation and different functional dependencies in the assumed heating term. Allowing these extra degrees of freedom to enter the problem simply increases the variations in $\langle T \rangle$ and $\langle P \rangle$ that would be expected in the corona, thereby increasing the degree of inhomogeneity. If separate populations of “cool loops” (e.g. Antiochos & Noci 1986) contribute to line emission, the degree of inhomogeneity will be higher still.

\textit{Observational status} Current observations may present something of a puzzle. High resolution NIXT and TRACE images show fine loop structures down to the resolution limits of the instruments ($\approx 1 \text{ Mm}$, see Figures 3 and 4). These can partly be understood in terms of the RTV laws and the assumed nature of $\mathcal{F}$. For a given $\mathcal{L}$, a spectrum of values of $\mathcal{F}$ at the foot-points\footnote{Assuming that the energy is injected along the field lines (via Alfvénic and slow magneto-acoustic modes). However, fast mode propagation across field lines and dissipation (Barnes 1968) may easily lead to loop-like structures because of field-aligned heat conduction.} will lead to a nest of fine loops whose intensities vary in rough proportion to $\mathcal{F}$ but whose temperatures are much more similar to one another (equations 6 and 4). Thus, if $\mathcal{F}$ varies by an order of magnitude over an active region, then we should see many fine-scaled loops of roughly similar temperature but different pressures and intensities, as seen in the LH panel of Figure 3.

High resolution and cadence observations at the base of $2 \times 10^6 \text{K}$ loops (Figure 4) reveal that the upper transition region plasma (near $10^6 \text{K}$) is highly structured and in contact with cooler chromospheric material (Berger et al. 1999). Thus, on observable scales, the interface between the base of the corona and the lower atmosphere is dynamic and spatially inhomogeneous, so we may expect $\mathcal{F}$ to reflect this.

On larger scales however, the corona seems to be well organized (see RH panel of Figure 3). This statement may come as something of a shock, given that we are all too familiar with the coronal fine structure. But the RH panel of Figure 3, shows that the Sun is often organized into large and physically separate volumes of material predominantly at different temperatures. This behavior might not be so easy to explain in terms of the RTV laws with reasonable assumptions on the distribution of $\mathcal{F}$ in lower layers, because such images would
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Figure 3. Left panel: structure seen at 171 Å in post-flare loops. Right panel: A false-color image of an active region observed with TRACE, taken from the TRACE image web site. The 171/195/284 bands are shown as blue/green/red (in color in electronic version), reflecting gas that emits Fe IX + Fe X / Fe XII / Fe XV respectively. Notice that the Sun has somehow organized itself to emit radiation from ions formed at different temperatures in physically distinct, large volumes.

The question of this section seems to place some peculiar constraints on $\mathcal{F}$. Further quantitative work on this point seems worthwhile. How can we reconcile the fine structure and the dynamic and inhomogeneous coronal base with and the large-scale temperature organization? Faced with these data, I am reminded of a piece of modern folk-lore, which says that a woman left her collie dog in her apartment a little longer than normal. Upon returning, the dog greeted her as usual, but she noticed that the apartment had been re-arranged so that all the movable plants were collected in one place, various newspapers, magazines etc. in another. The dog had become bored and had re-organized the apartment, reducing the apparent entropy by increasing the order on observable scales. Is there a need to invoke a collie dog on the Sun?

**Poynting flux and dissipation** Section 3.2. shows that the question concerning the homogeneity of the plasma has thus been translated into a discussion concerning the homogeneity of $\mathcal{F}$ and its divergence along a given loop. We know that mechanical energy generated by the turbulent atmosphere and convection zone is channelled into the upper solar atmosphere via both acoustic waves and electrodynamic processes, and that coronal heating is dominated by the latter (e.g. Narian & Ulmschneider 1990). Magnetic heating is fundamentally a difficult problem. Energy is directed towards the corona in the form of a Poynting flux $\mathcal{F}_P = \frac{c}{4\pi} E \times B = -\frac{1}{4\pi} (\mathbf{U} \times \mathbf{B}) \times \mathbf{B}$. Dissipation of this energy must occur in the MHD limit (at frequencies $\ll$ the characteristic ion cyclotron frequency) either through Ohmic ($\mathbf{j} \cdot \mathbf{E} = \text{curl}^2 \mathbf{B}/\sigma \sim B^2/(\ell^2 \sigma)$) or viscous heating, both of which must occur on tiny physical scales $\ell$. At much higher frequencies, wave-particle interactions are expected to contribute to the dissipation, again on small physical scales. Heating occurs when $\text{div} \mathcal{F}_P < 0$. 

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Figure 4. (A) Ca II K-line image, bright areas demarcate the location of magnetic elements in the lower chromosphere, red contours outline the regions of bright moss emission defined from the TRACE 171 image shown in C. (B) Same region seen in a summed image of Hα -350 and +350 mA filter-grams, green contours (in color in electronic version) outline dark areas of increased absorption which demarcate transient "jets" of chromospheric plasma. (C) TRACE Fe IX/Fe X 171 Å image. From Berger et al. (1999).

More detailed MHD models of dissipation (e.g. Davila 1991, Galsgaard & Nordlund 1996) confirm that magnetic dissipation (div $\mathcal{F}_\mathcal{P} < 0$) occurs on very small physical scales that are far below the limit ($\approx 1$ Mm) of current observations. We are thus led again to the question: is there some way that the dissipated energy can fill up a large volume across field lines so that the plasma may be expected to be homogeneous?

**Cross-field energy transport** Litwin & Rosner (1993) considered cross-field energy transport in the corona. This careful study revealed no reasonable mechanism by which energy dissipated over tiny volumes can be efficiently distributed across field lines. If cross-field energy transport is negligible in reality, then $\mathcal{F}$ and its divergence will have very fine scale structure across observable volumes. Then one must expect a very inhomogeneous situation, as sketched in Figure 4 of Judge & McIntosh (2000). Each "building block" may be gyro-radii (i.e. meters, not Mm) thick, each "loop" of length L consists of many filamentary "loops" with their own $\langle T \rangle$, $\langle P \rangle$, so that there is there is no unique $\langle T \rangle$ or $\langle P \rangle$ even for one "resolved" loop, and plasma diagnostic techniques will fail. But some order is probably missing from this picture, because there would be so much small-scale structure that there would be little to differentiate obviously separate volumes of the corona, which seems to occur (Figure 3). Perhaps (1) an efficient, yet to be identified, mechanism transporting heat across field lines in

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lower in the atmosphere make \( F \) and its divergence uniform over large spatial scales. For example, photospheric “flux tubes” of diameter 0.2 Mm may expand to \( \approx 2 \) Mm at the base of the corona. If \( F \) is uniform within a flux tube it will be uniform over \( \approx 2 \) Mm in the corona, or (3) \( F \) contains such small scales it is effectively uniform enough to make, via the loop scaling laws, \( \langle T \rangle \) or even \( \langle P \rangle \) uniform over observable volumes.

Figure 4 suggests that cross field conduction challenges our understanding not only of the corona but also of the transition region. Is the observed transition region really formed in a thermal interface between chromosphere and corona, or is it dominated by emission from magnetically and thermally isolated structures? Current studies remain inconclusive, despite bold claims (e.g. Feldman et al. 1999), because the cross-field heat conduction problem has not been solved. Parameter studies of isotherms by Athay (1990) and Ji et al. (1996) suggest that it may provide a resolution to this question, and may even explain the invariant shape of the emission measure distribution.

4. Conclusions

Photon spectra obviously contain highly convoluted and integrated signatures of the physical conditions in the emitting plasmas. An accurate diagnosis of such conditions requires additional information. Using examples based on synthetic data, I have argued that physical parameters derived from popular “spectral diagnostic techniques” are determined not by the data alone but mostly by the underlying assumptions (including liberal close shaves with Occam’s Razor) which may or may not have support from physical considerations. The “additional information” that renders the diagnosis “unique” comes from the assumptions – which may or may not even be verifiable – a disquieting situation. Furthermore, I reviewed evidence that systematic errors arise when inhomogeneities are present, and showed that the line-ratio and inversion techniques fail to confirm or falsify a hypothesis (that the plasma consists of two components at just two different pressures) that is just one step away from homogeneity. The central issue of the homogeneity of the plasma was reviewed from a theoretical and observational perspective, and although simple reasons exist to suppose that isothermality might be a reasonable approximation, there is no reason to suppose that the plasma in observable volumes will satisfy isobaric conditions. Thus, simple line-ratio techniques are expected to fail and be misleading.

I conclude that mis-interpretations, systematic errors, and invalid conclusions can be drawn from common, apparently reasonable approaches to diagnosing physical conditions in the unresolved plasmas that comprise solar and stellar coronae. This hardly seems like a “small caveat” (Laming 1998) to me – but non-uniqueness reigns and the size of this caveat cannot be determined either. . . . The only safe way to proceed is to add information through what we know of the underlying physics, which probably means building forward models.

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