X-ray Diagnostics for Supernova Remnants

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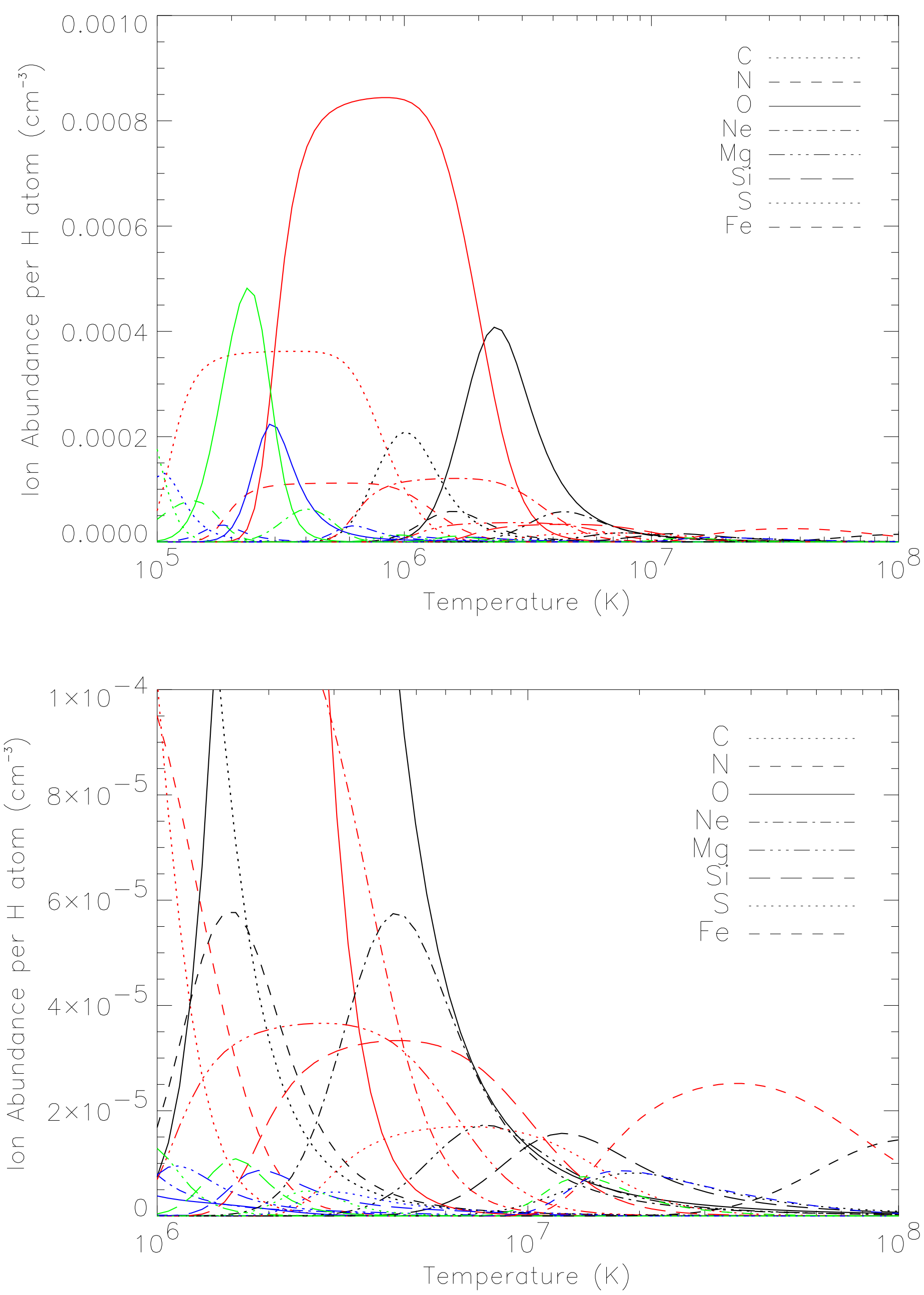
The text of this talk is available at
http://hea-www.harvard.edu/ rsmith/xraydiag.ps

What answers do astronomers want from supernova remnants (SNRs)?

- What is the environment do they explode into like?
- What are the physical interactions at the shock front
- What is the physical state of the ejecta?
- What is left behind?
- What processes govern the late-term evolution?

How can we get these answers? Fortunately for X-ray astronomers, most of the emission from SNRs comes in the form of X-rays. Unfortunately, with the loss of Astro-E, we must primarily use CCD imagers, except for those SNRs small enough to do useful grating observations with Chandra or XMM/Newton. Therefore we can only measure strong lines, observable even when substantially broadened.

As a result, the primary diagnostic emission lines are from hydrogenic and helium-like ions. Part of the reason why can be seen below:



The emissivity of a given transition line $\lambda_{j\rightarrow i}$ is simply

$$\epsilon = \frac{hc}{\lambda_{j\rightarrow i}} N_j A_{ji} \tag{1}$$

where N_j is the population of level j and A_{ji} is its transition rate. Nice and easy.

Tragically, however, calculating N_j is not necessarily an easy manner. Consider the possible methods of populating level j:

Electron collision	$e + I_{gr} \rightarrow e + I_j$
Proton collision	$p + I_{gr} \rightarrow p + I_j$
Radiative recombination	$e + I^{+}_{gr} \rightarrow I_j$
Radiative transition	$I_k \rightarrow I_j + \gamma$
Dielectronic transition	$e + I^{+}_{gr} \rightarrow I^{*}_{n} \rightarrow I_j + \gamma$
Innershell excitation/ionization	$e + I^{-}_{gr} \rightarrow 2e + I_j$

And then there are the depopulation methods:

Electron collision	$e + I_j \rightarrow e + I_{gr}$
Proton collision	$p + I_j \rightarrow p + I_{gr}$
Radiative transition	$I_j \rightarrow I_{gr} + \gamma$

In collisional ionization equilibrium, we assume that the ion abundance is constant and so can solve for the level population by simply balancing the rate equations between the levels while requiring the level population to sum to unity.

However, in the case of a supernova remnant, equilibrium may be a poor assumption, and a time-dependent method must be used. In this case, the true solution is to assume only that atoms are conserved, and solve for the level population of all the ions at once.

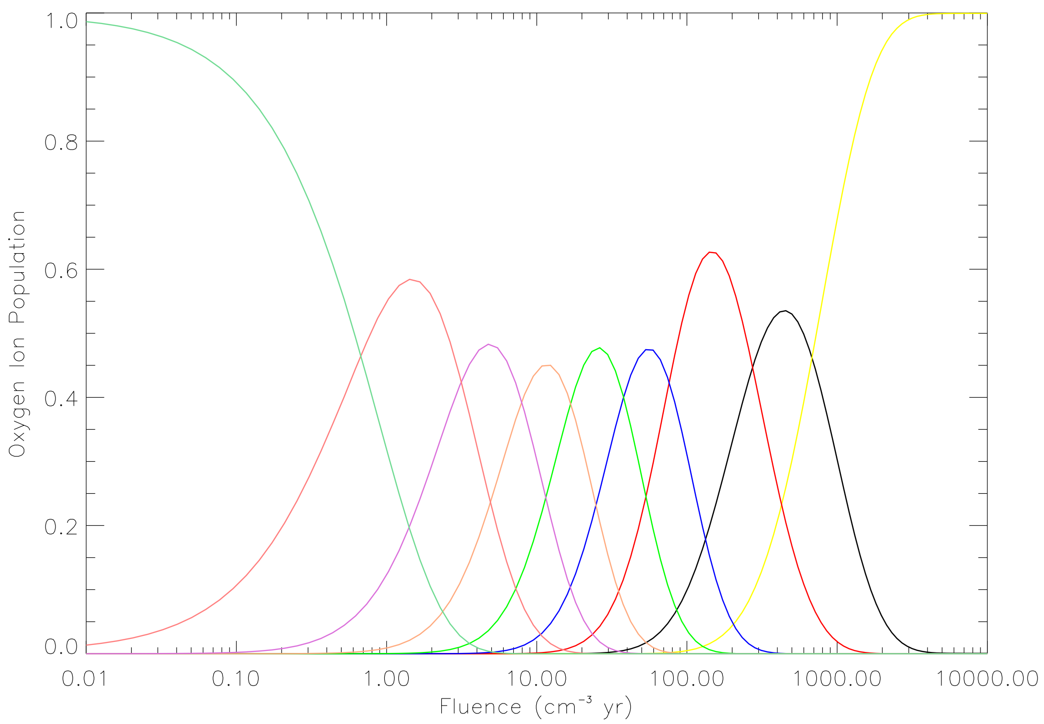
This is usually *not* done, because the total ion-to-ion rates are generally known to better accuracy than the per level rates. Instead, a two-step approach can be used:

1. evolve the ionization state and
2. Solve for each ion's level population using the ion balance from (1).

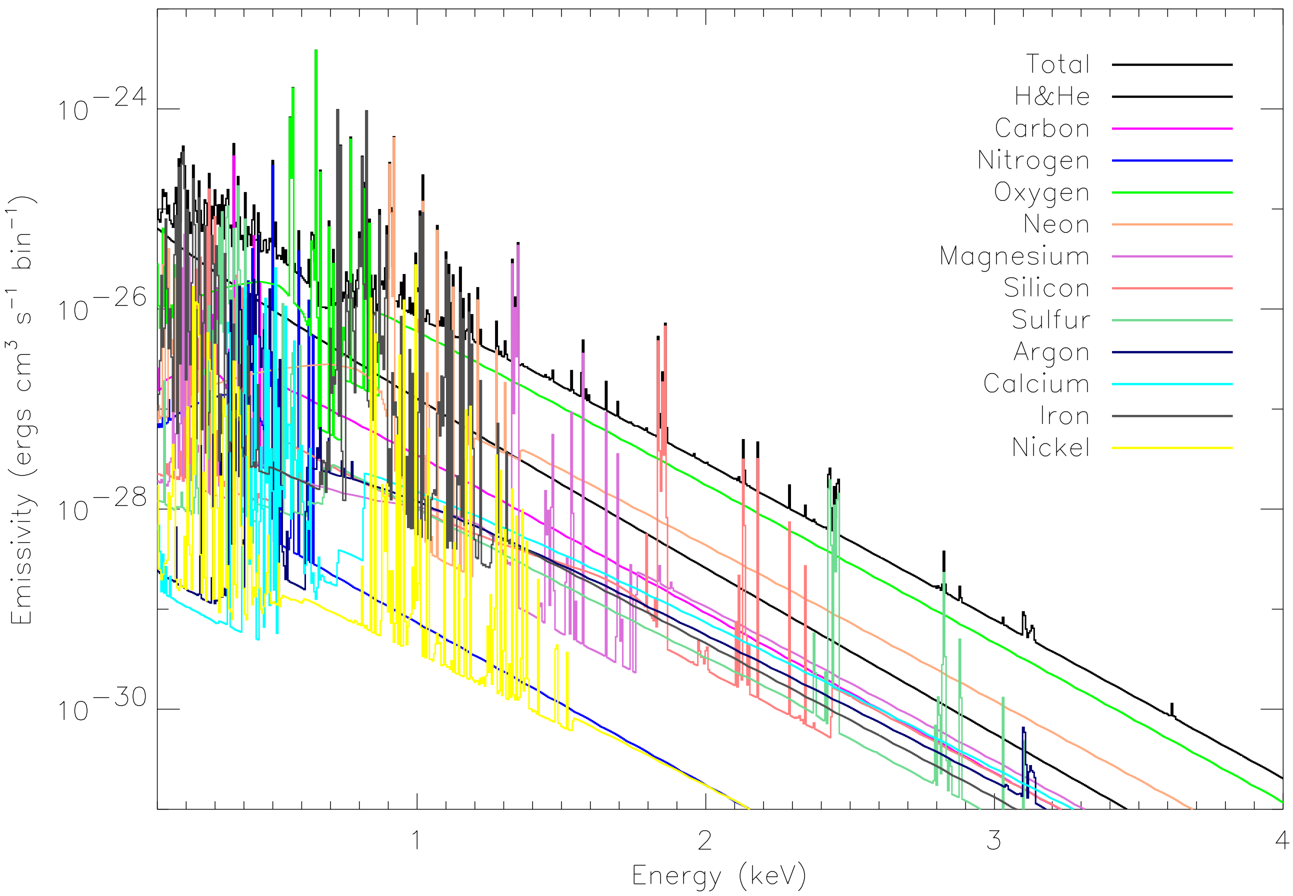
Note: Since all of the atomic rates in question are proportional to time and electron density, it is convenient to use the fluence, defined as

$$f = \int n_e(t)dt \tag{2}$$

as the dependent variable for non-equilibrium ionization situations.

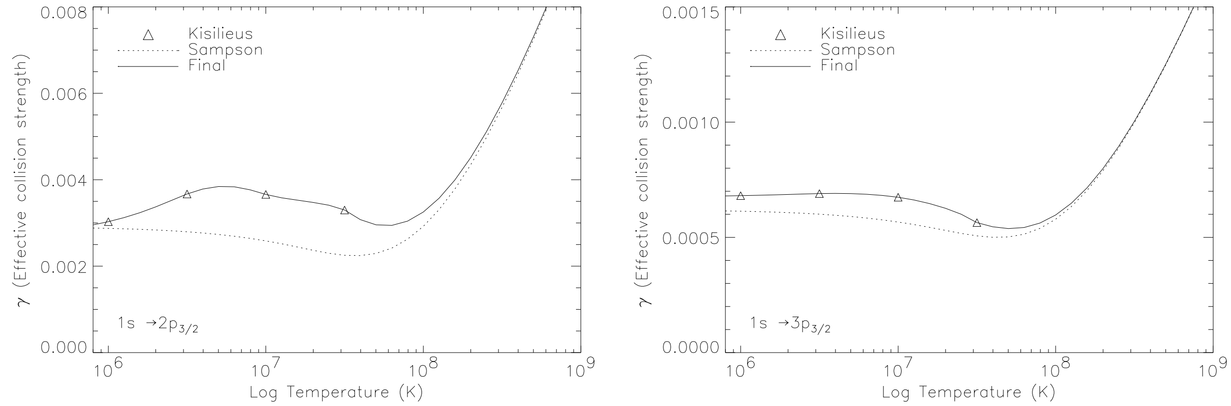


Shown here is the X-ray spectrum of a CIE plasma at 3×10^6 K, with each element shown as a different color. Note that each ion emits only a few strong lines–so only these will be significant when doing a variable abundance fit.



With the improved spectral resolution of Chandra and XMM/Newton we will be able to extract these individual strong lines from the spectrum–admittedly with large errors at times Diagnostics are usually created from line ratios, since they are much cleaner than whole-spectrum fits.

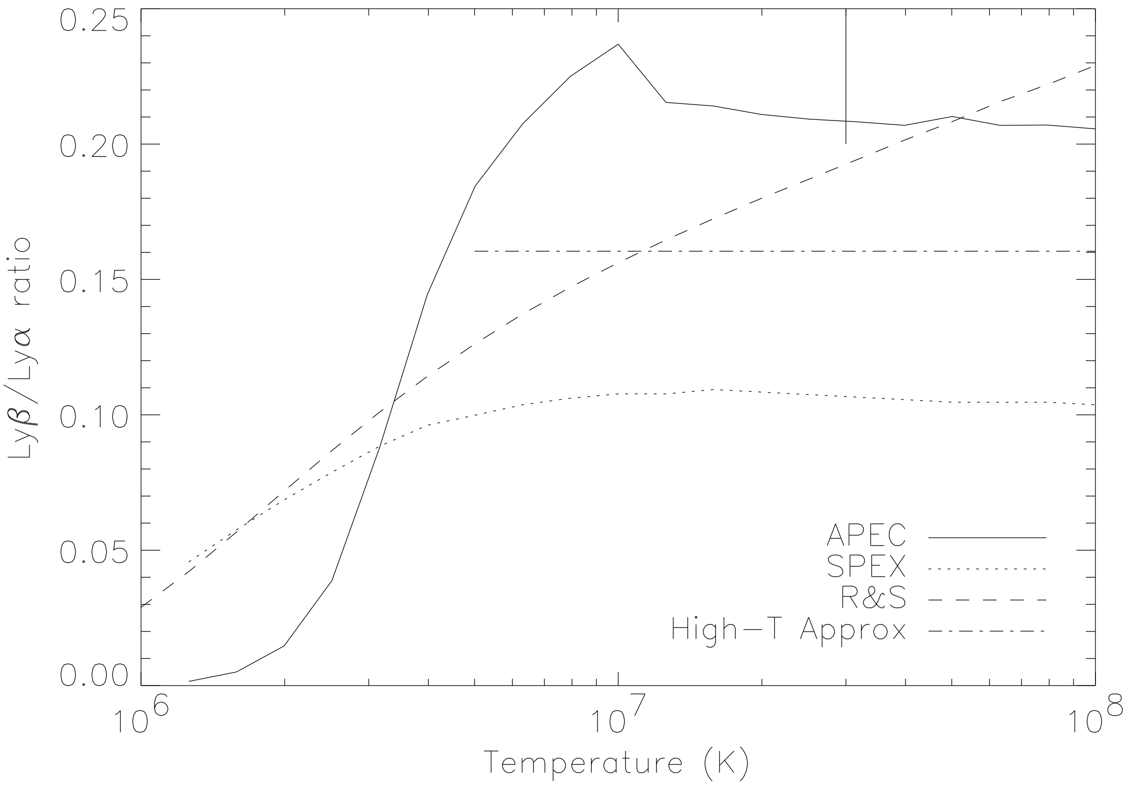
The energy levels and bound-bound transition rates for hydrogenic systems can of course be solved exactly, which leads people to the common fallacy that the collisional rates should be equally straightforward. This is **not** the case; in fact, collisions in hydrogenic systems are very difficult to calculate.



The difficulty is due to the fact that the first excited state is 3/4 of the ionization energy. A free electron with enough energy to excite the first bound state probably has enough to ionize the ion, and so the quantum calculation must incorporate the infinite number of unbound states in its calculation. Methods exist to do this (e.g Igor Bray's work), but data doesn't yet exist in the form we need.

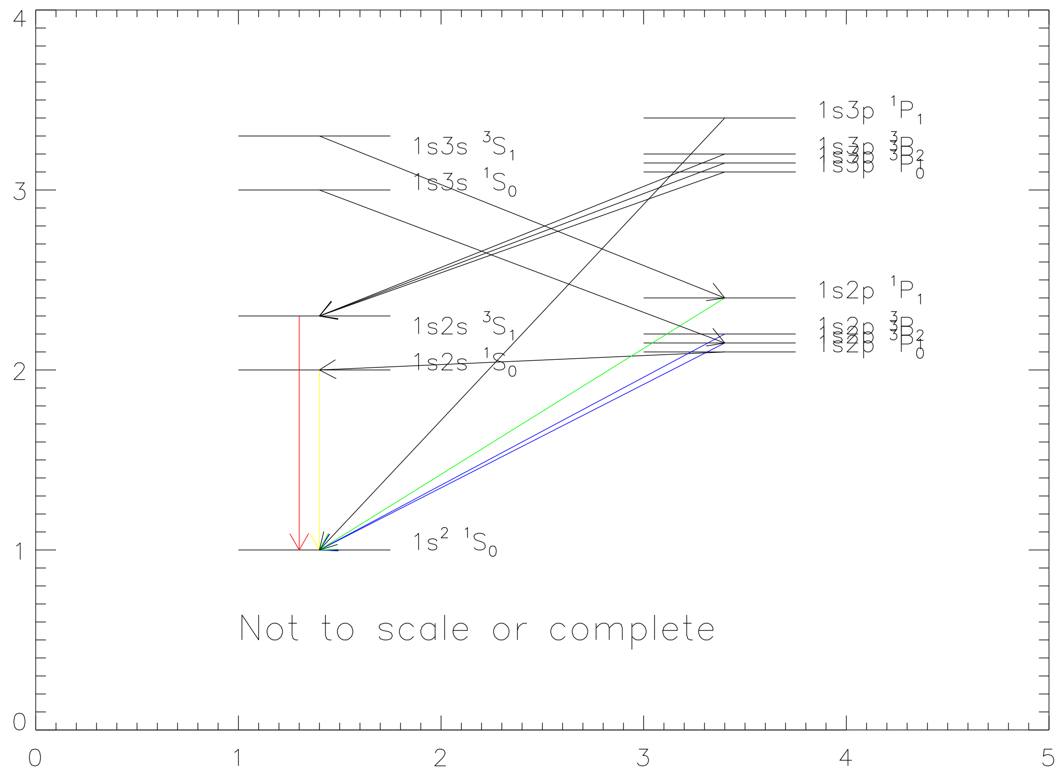
The strong X-ray lines from hydrogenic systems are the $np^2P_{1/2,3/2} \rightarrow 1s^1S_{1/2}$ transitions. Of course, the $np^2P_{1/2}$ and $np^2P_{3/2}$ states of hydrogenic ions are not degenerate in practice, but even in iron they are only 21 eV apart ($R \sim 330$)

This leaves us with the ratios of the strong $np \rightarrow 1s$ transitions, which should make for excellent temperature diagnostics since they are independent of ionization balance. However, there are still a few problems:



The glitch in the APEC line ratio is due to the merging of the Kiselius and Sampson data.

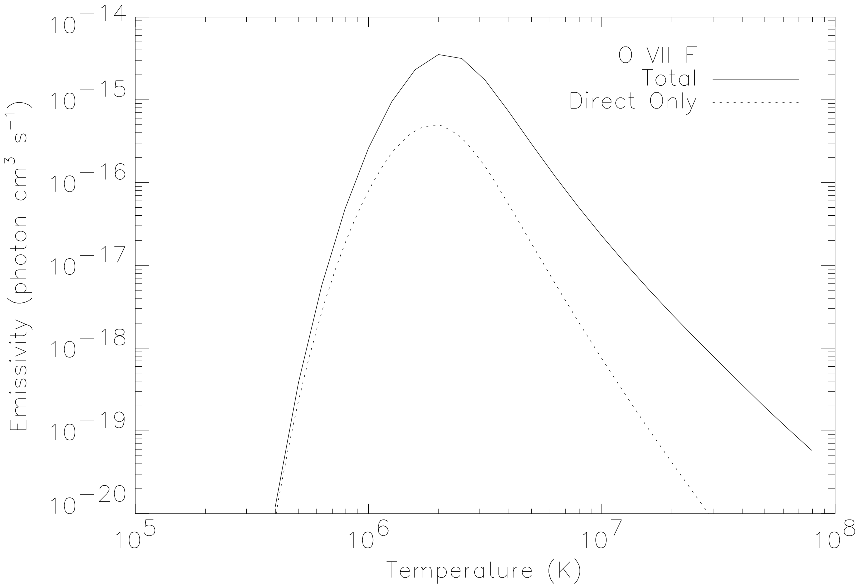
Helium-like ions have the well-known "triplet" of lines, which are shown in this energy level plot:

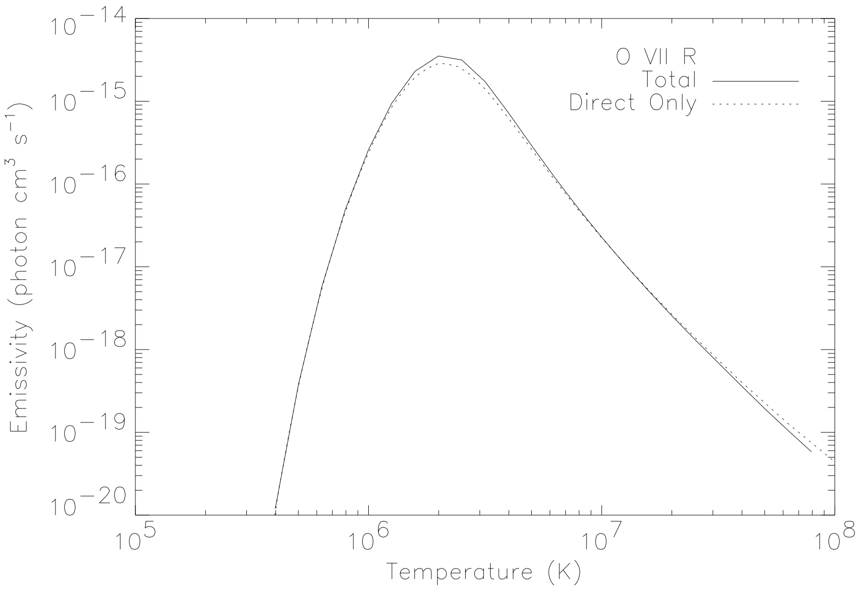


The forbidden (F) line is shown in red, the resonance (R) line is in green, the two intercombination (I) lines are in blue, and the two-photon transition is shown in yellow. The "helium triplet" is really four lines, and is associated with five separate energy levels.

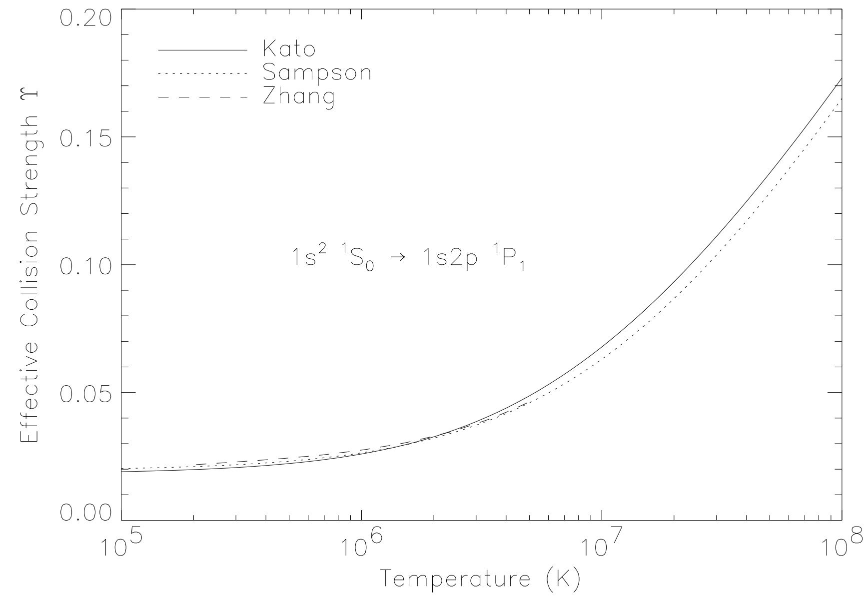
Fun fact: the transition rate for the two-photon transition in oxygen is ~ 1000 the rate for the forbidden transition.

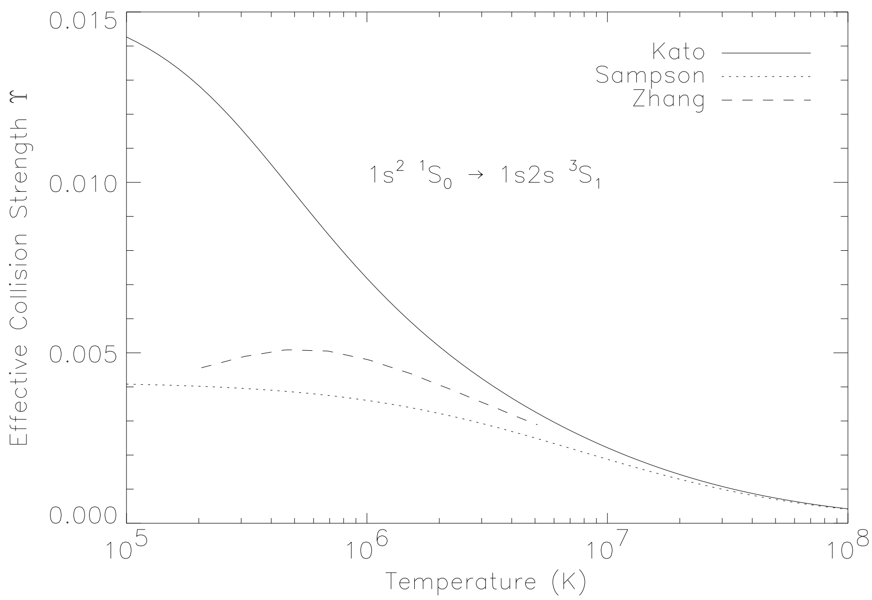
If they can be separated, the F, I, and R lines are very useful diagnostics. One reason why is shown here:





The calculated resonance line emissivity can be completely explained using only electron collisions. However, the same is not true for the forbidden line, which is also populated by recombinations, and by transitions from other levels, even in equilibrium. In NEI conditions, the effects can be even stronger.

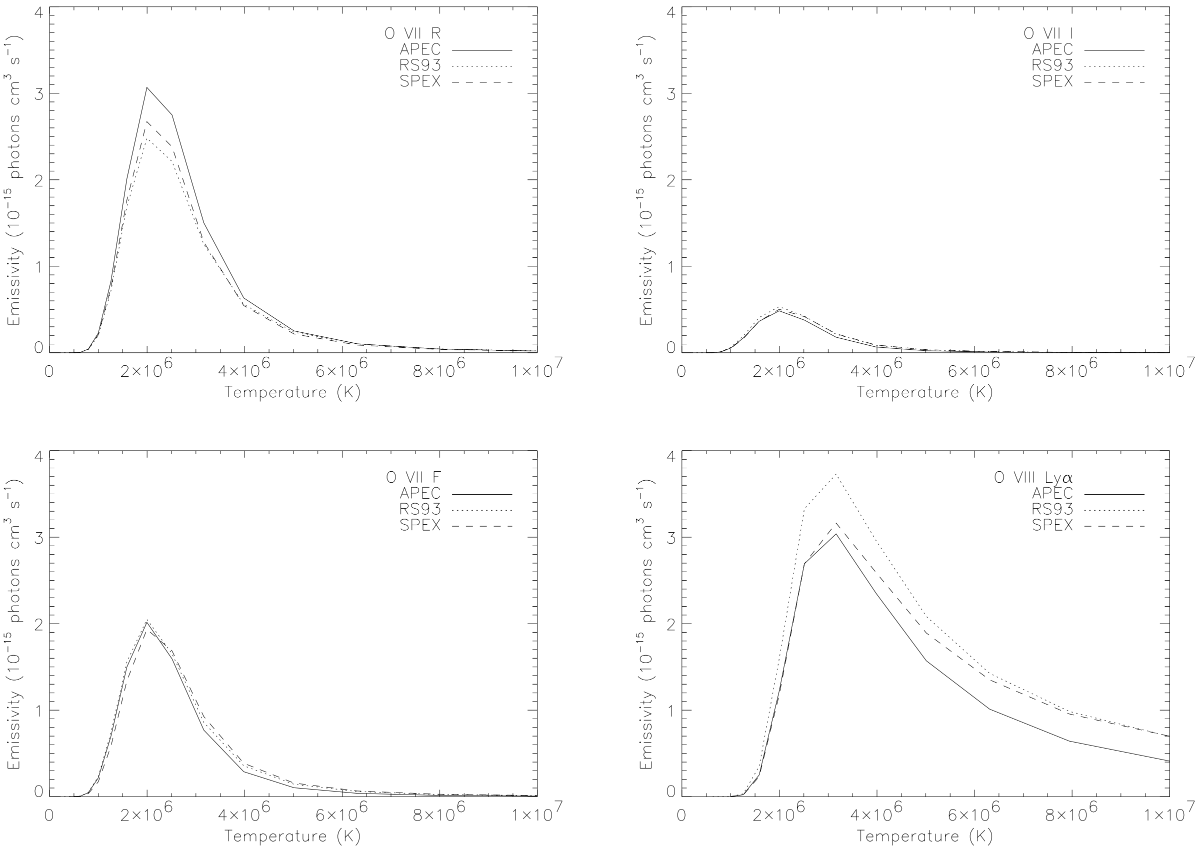




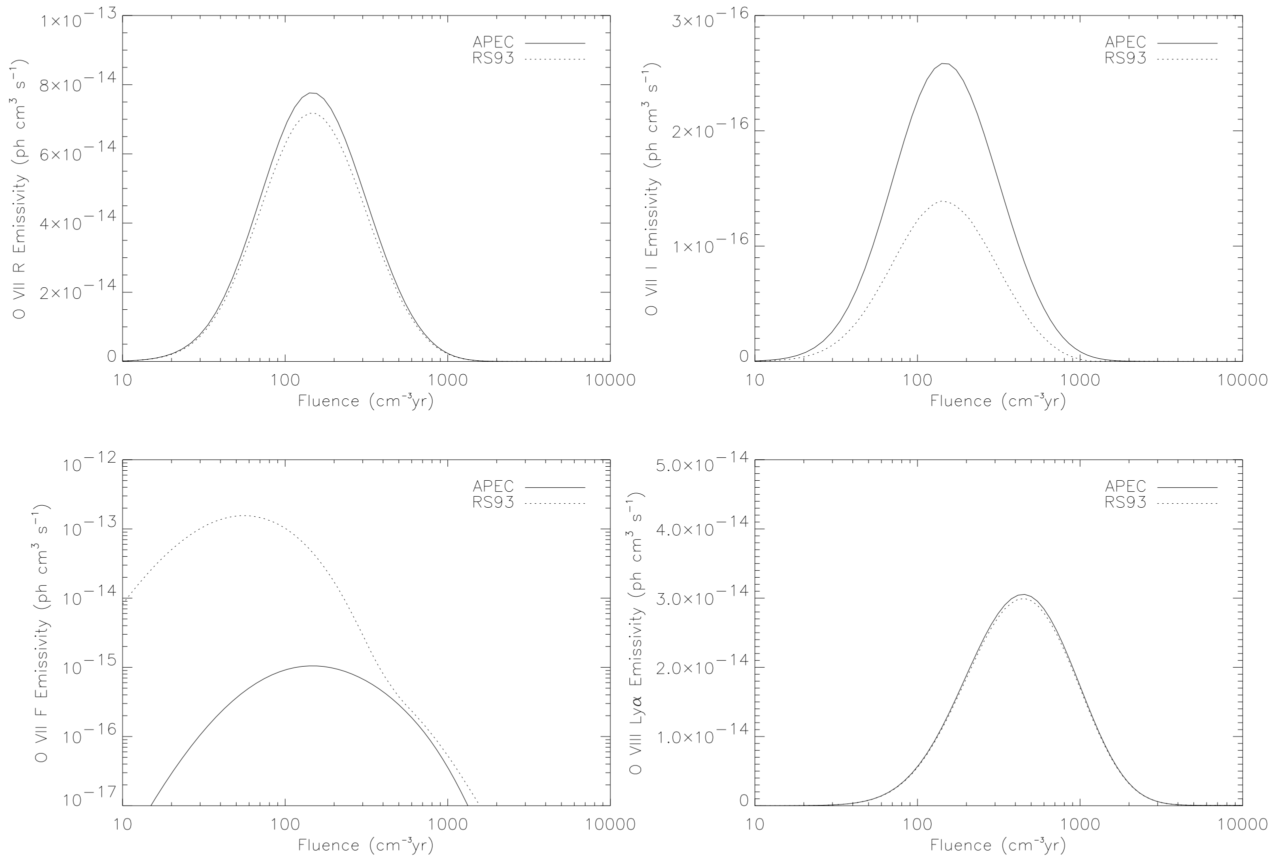
The collison strength for the O VII $1s2p^1P_1 \rightarrow 1s^{2\,1}S_0$ (R) line is not strongly affected by resonances. However, the same is not true for the forbidden transition, $1s2s^3S_1 \rightarrow 1s^{2\,1}S_0$.

In equilibrium, the line emissivities for the very strongest lines of hydrogenic and helium-like lines are fairly well-measured.

Here, I comparing the APEC, SPEX, and Raymond & Smith predictions for the O VII triplet and the O VIII Lyα line.

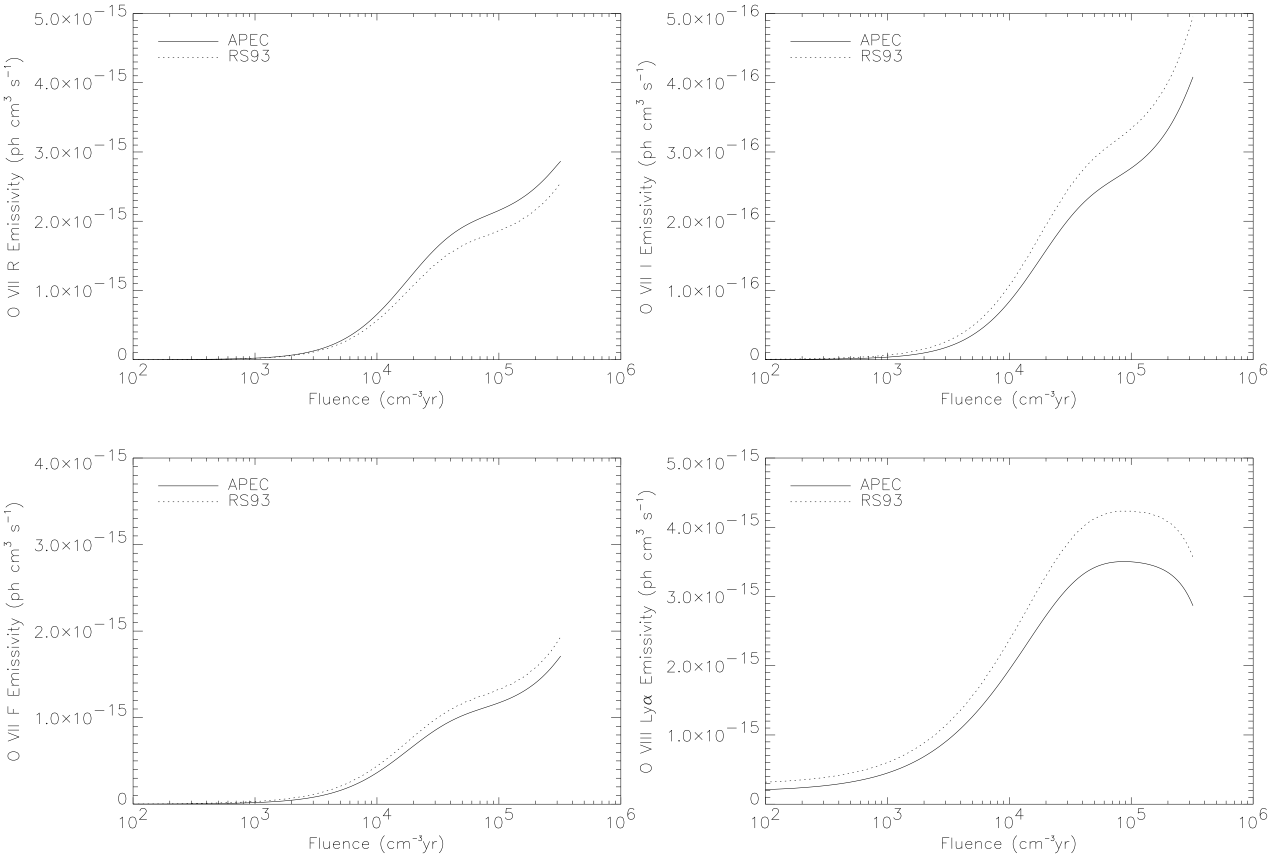


APEC and Raymond & Smith predictions for the O VII triplet and the O VIII Lyα line for a shocked plasma. In this case the ion temperature is 10^4 K, and the electron temperature is 10^8 K. The ionization balance in both cases was calculated by the Raymond & Smith code; APEC only calculates line intensities.

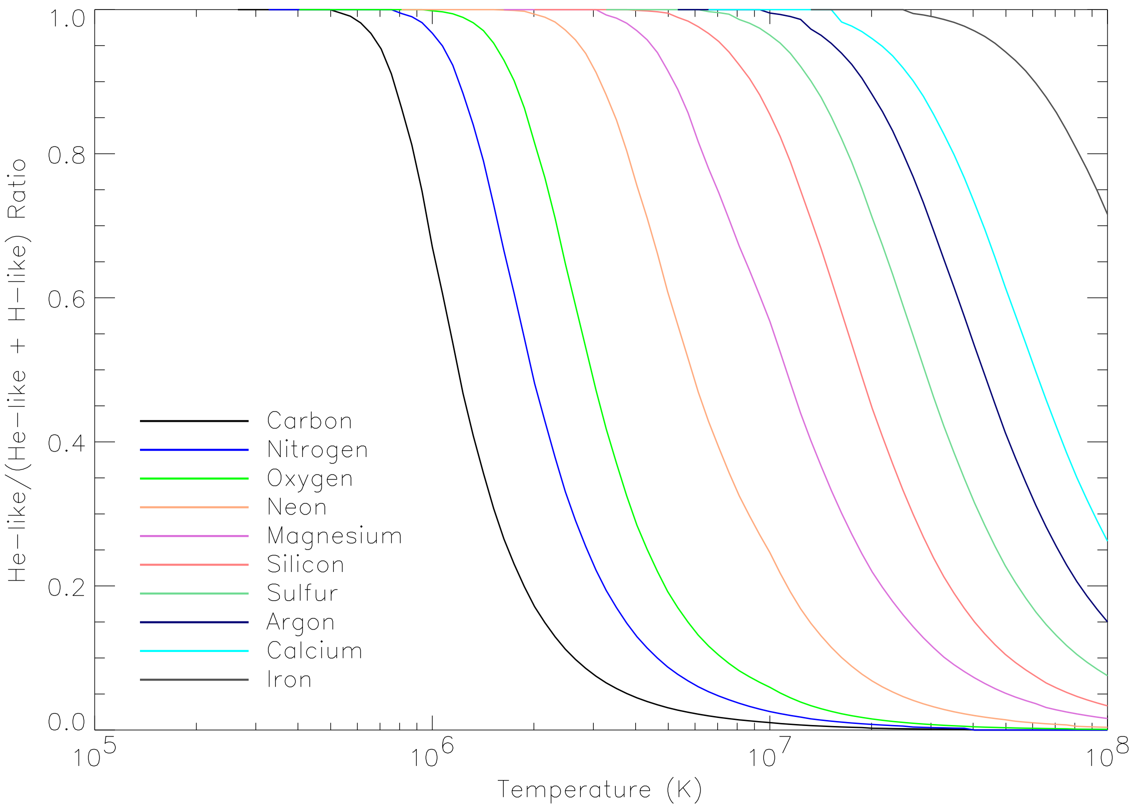


The lines match reasonably well except for the forbidden line. This is due to the lack of innershell ionization/excitation rates in APEC. The RS93 code shows a peak in the F emission at early times due to Lithium-like O VI losing a K shell electron, giving a O VII ion in the 1s2s state.

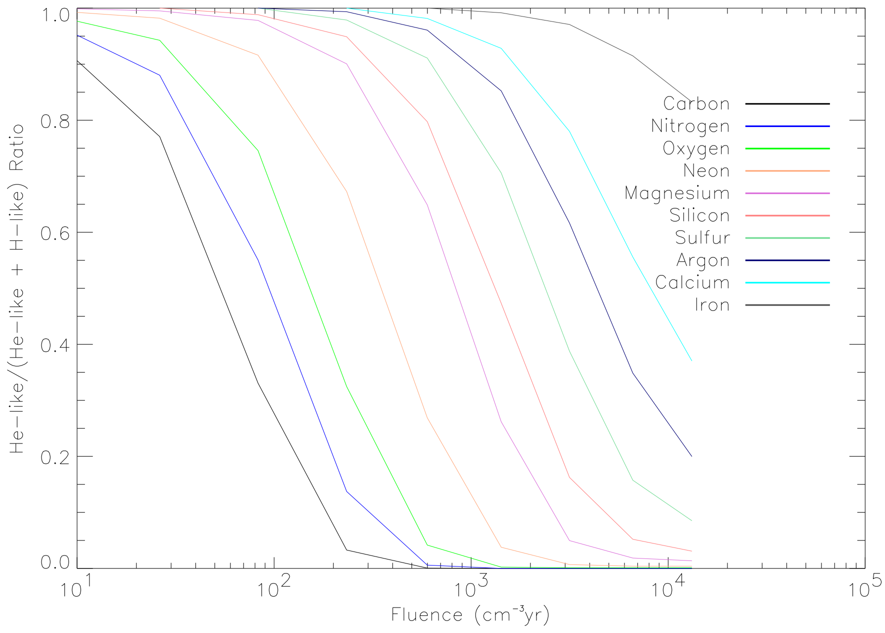
APEC and Raymond & Smith predictions for the O VII triplet and the O VIII Lyα line for a recombining plasma. In this case the ion temperature is 10^8 K, and the electron temperature is 3×10^6 K. The ionization balance in both cases was calculated by the Raymond & Smith code; APEC only calculates line intensities.

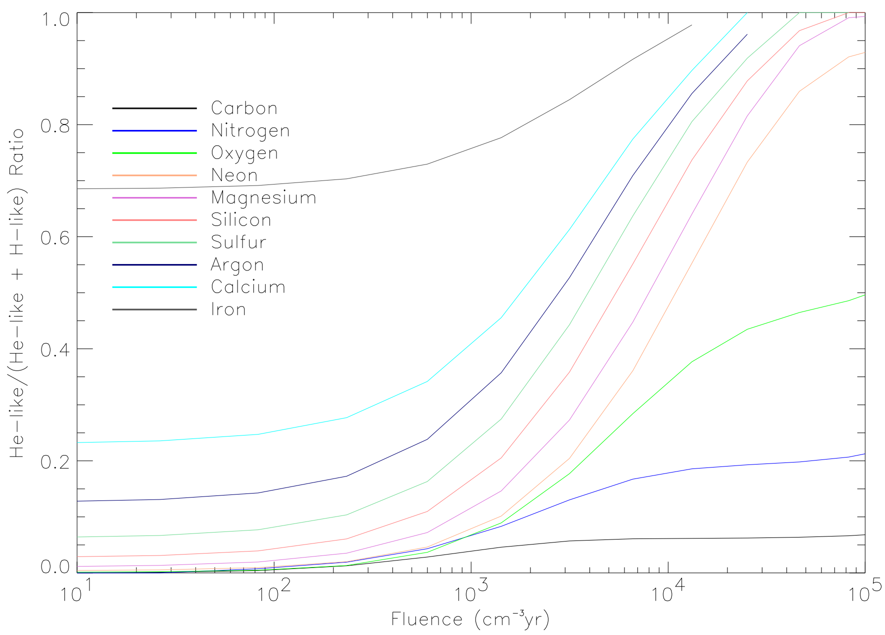


In many cases, the best that can be done is to compare the hydrogenic lines to the helium-like. However, at least the dependence on abundance (and with it questions of ejecta and dust formation/destruction) drops out. Line ratios from these ions are however functions of both temperature (as shown here for the equilibrium case) and ionization balance.



Of course, the hydrogenic and helium-like line ratios depend upon the ionization state. Shown here is the ratios for a shocked plasma and a recombining plasma:

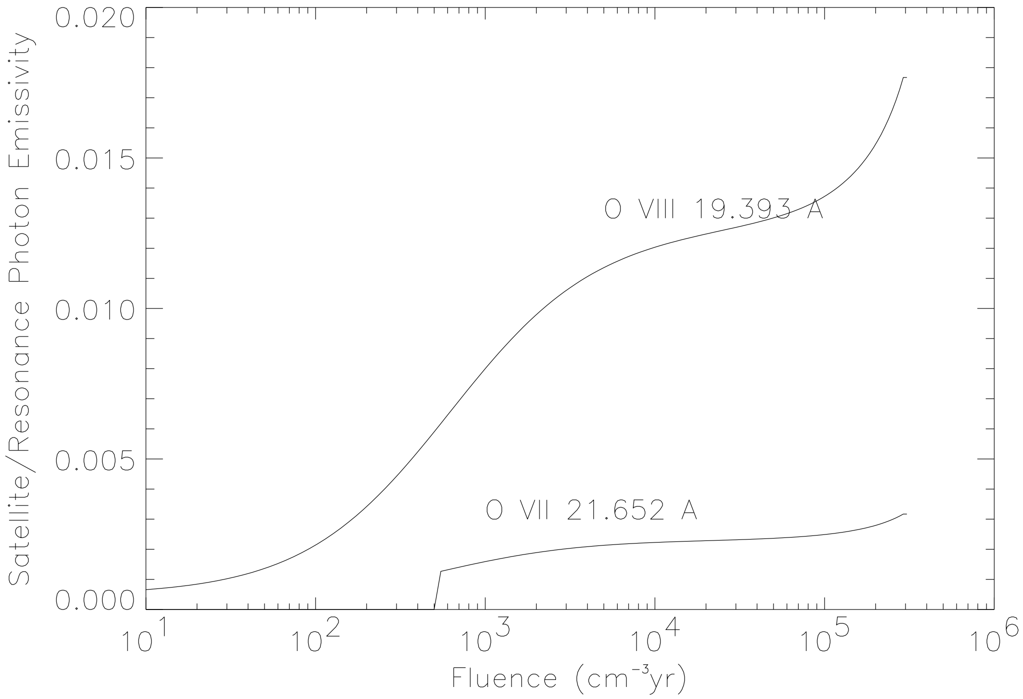




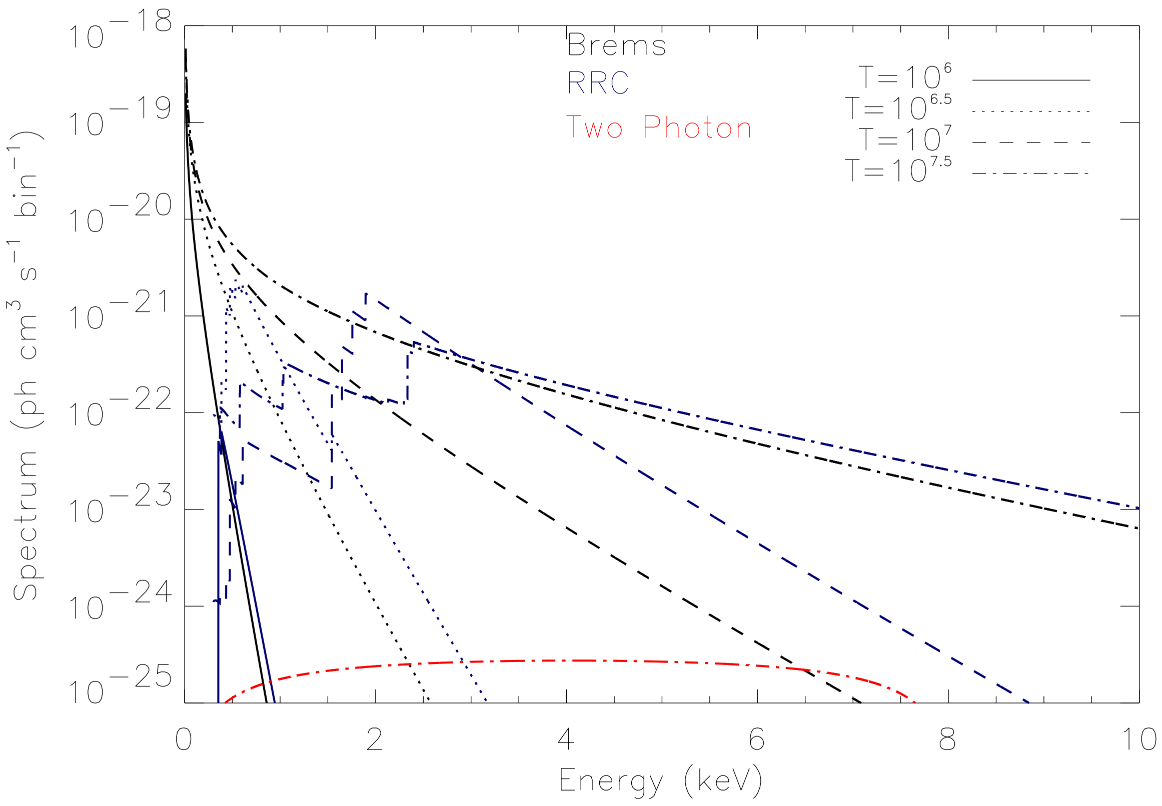
Dielectronic recombination occurs as follows:

$$e^- + I^+ \rightarrow I^{**} \rightarrow I^* + \gamma_{\mathrm{satellite}} \rightarrow I + \gamma \tag{3}$$

The "satellite line" is emitted while the ion is in a doubly-excited state. The wavelength is therefore at a longer wavelength than the normal transition, due to the other excited electron. In a recombining plasma, if the electrons are cold ($E_{\mathrm{electron}} << E_{\mathrm{ionization}}$) recombination occurs primarily via radiative recombination. If they are warmer, then dielectronic recombination is frequently stronger. Satellite lines make for simple temperature diagnostics in a recombining plasma, but they will be challenging for SNR use, even if they can be separated from the main line. Shown below is the strongest hydrogenic and helium-like DR lines, relative to the resonance lines, in a recombining plasma:



Bremsstrahlung (aka free-free radiation) can be used to measure the temperature of electrons in a hot plasma, although in many circumstances radiative recombination may be a larger contribution:



Above 1 keV, there are a number of places in the spectrum where pure continua can be extracted–there just aren't that many lines up there. In either case, both the RRC and Brems have simple temperature dependencies.

Fun Fact: The bremsstrahlung model in XSPEC and sherpa is not explicitly relativistic, but differs by less than 2% from a fully relativistic treatment.

And now, summing up with things both said and unsaid:

- It's a crying shame Astro-E didn't survive.
- Line ratios are far cleaner, and with Chandra/Newton CCD resolution, worth extracting.
- Modelling an ionizing plasma requires ionization rates and the high-T behavior of excitation rates. These are fairly well-known.
- Modelling a recombining plasma requires radiative and dielectronic recombination rates, as well as the near-threshold behavior of excitation rates. These are extremely poorly known.
- Using DR lines for SNR diagnostics will not be possible anytime soon, except possibly for SNRs small and bright enough to be done with gratings.
- Fitting the continuum above 1 keV is a decent way to get a baseline electron temperature.