Analysis of spectra from theoretical model HII regions.

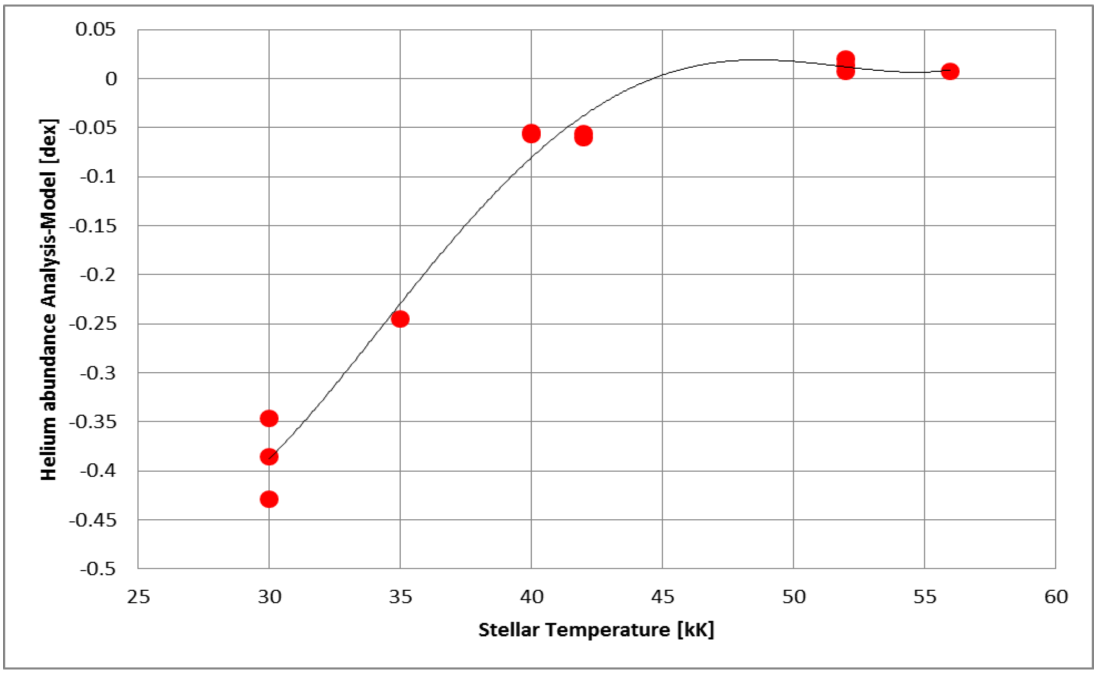
General remarks:

- Better plot results with the proper values for the abscissa, and not as the sequence of abscissa values, which seems to be the standard option in programs like Excel … 40000K and 42000K are closer together than 30000K and 40000K!
- Recommendation: always look for tendencies in data; check the cases with large deviations from a general trend: it might indicate an error or it may have an interesting reason!
- when you want to show differences, plot them directly! Showing superposed curves may not be helpful. Also, since helium has such a high abundance, it is better to plot its results separately from the other elements.

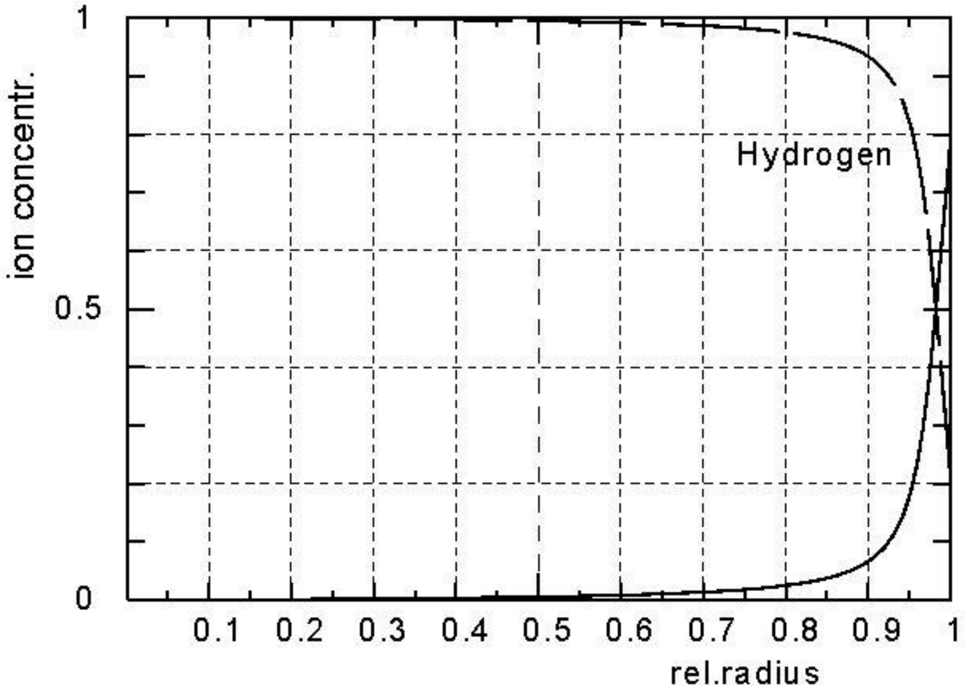
Helium:

There is a systematic behaviour … some of you spotted it. However, if one plots all elements in one graph it makes it harder to see.

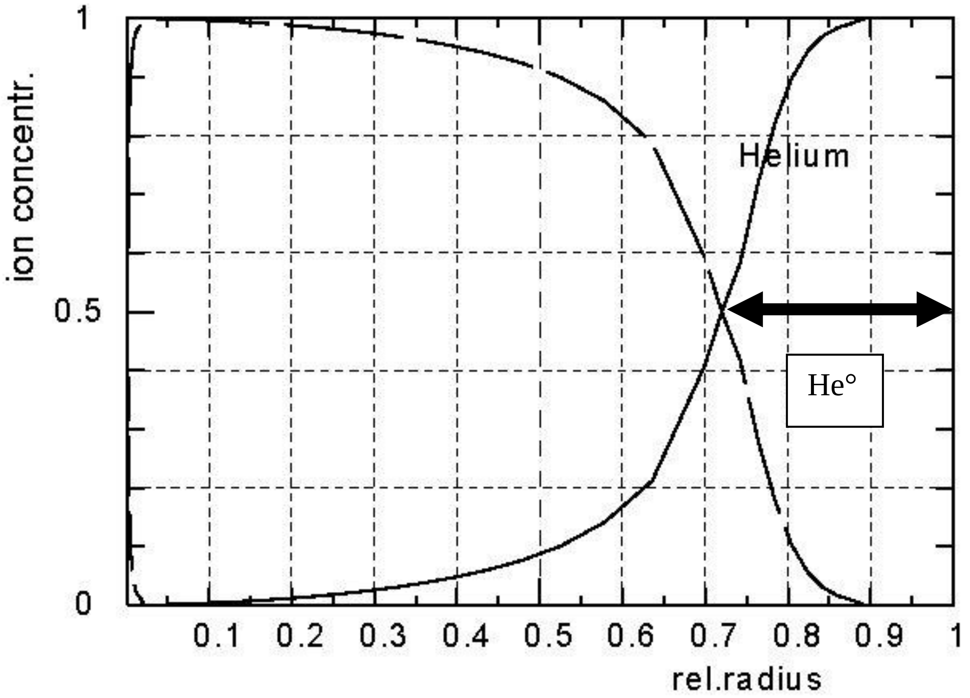
1. The errors on the He/H abundance ratio are usually quite small, about 0.01 dex. You noticed this … but there is also a physical reason: the He and H lines are **recombination lines** whose emissivities do not depend strongly on the electron temperature of the gas. Hence, any uncertainty in the temperature determination does not affect the He/H abundance very much!
2. However, at low stellar temperatures, we see that our values are always **smaller** than the true values:



There is a simple reason for this: stars cooler than about 40000 K cannot ionize helium sufficiently strongly, so that the outer portions of the HII region helium are neutral. This volume does not contribute to the emission of the HeI recombination lines at e.g. 5876, and so we do not measure the whole amount of helium. The figures below show the ionization around a 30000K star, for hydrogen



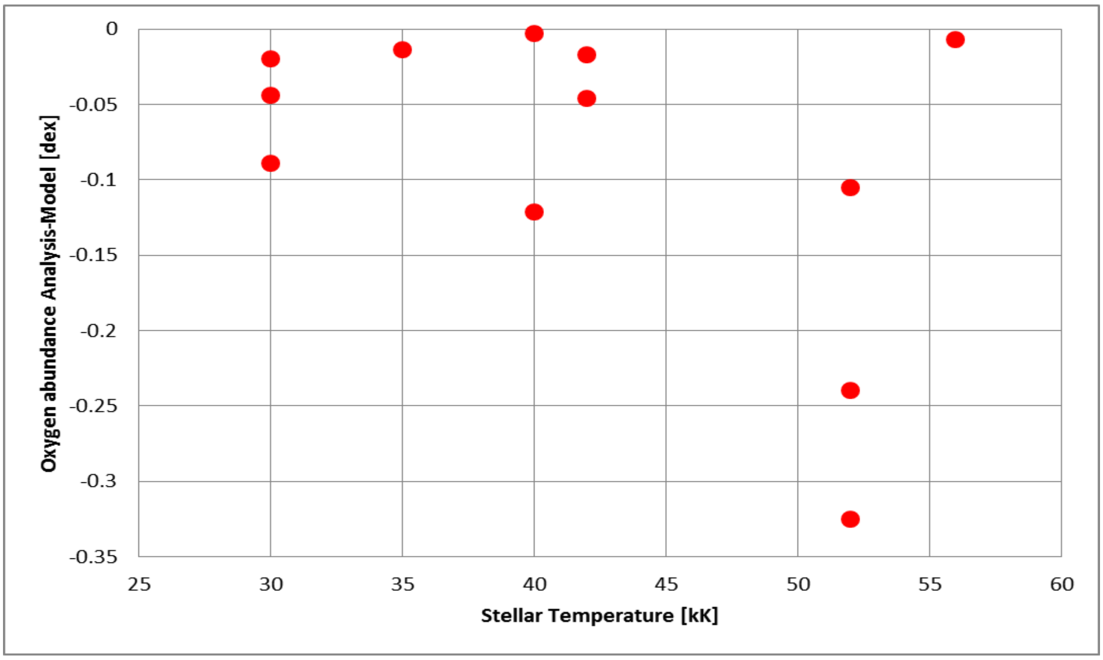
and for helium:



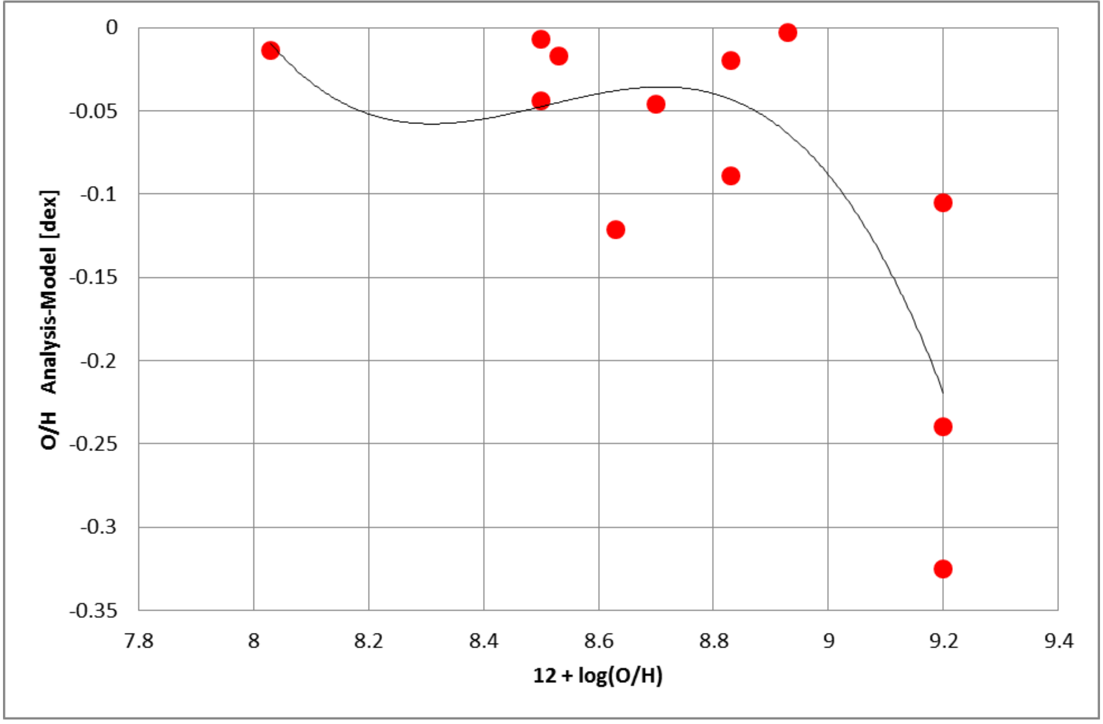
Unfortunately, the amount of neutral helium cannot be measured: the He I lines are produced by recombination and thus measure the content of singly ionized helium!

Oxygen:

The errors for the oxygen abundances are generally quite low: less than about 0.1 dex … which is about 25 percent.

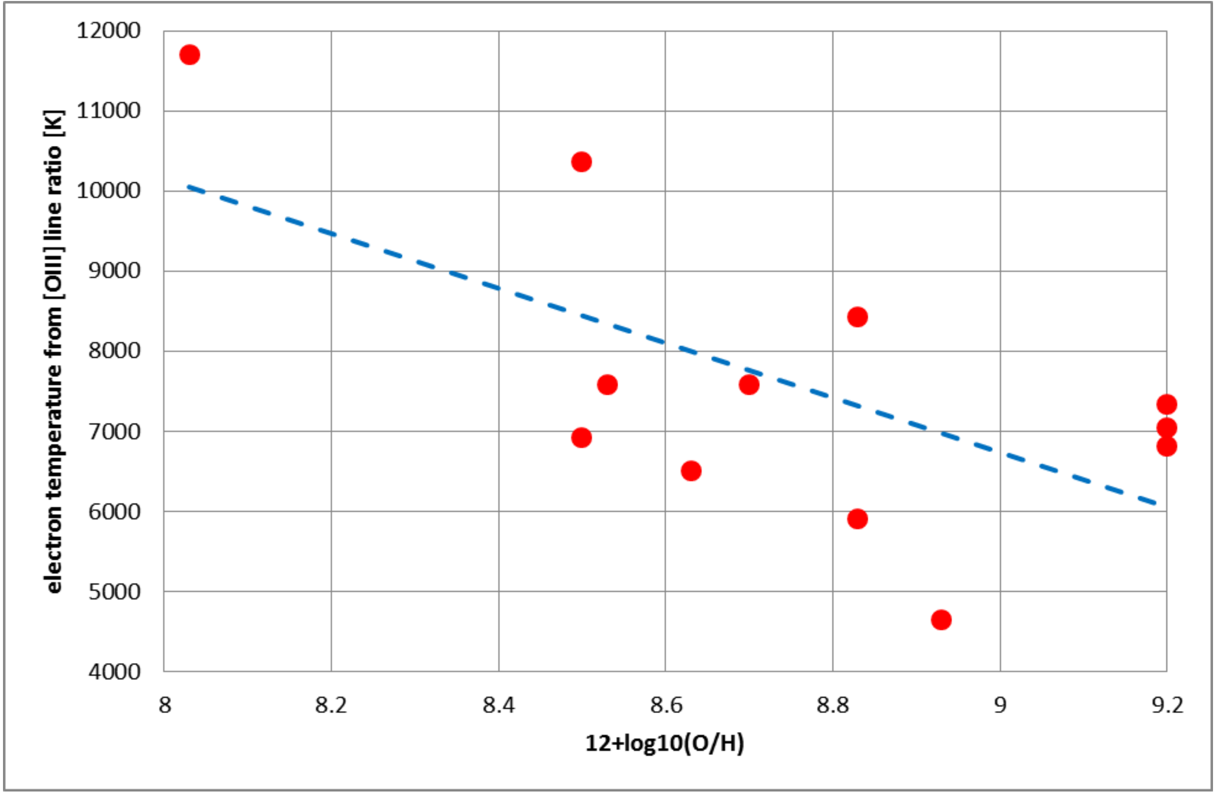


However, there are three exceptions: the 52000K results of Emmanuelle, Orianne, and Simon results show large deviations of -0.24, -0.11, and -0.33 dex. What's happening here? In these cases, the assumed oxygen abundance is rather high (9.2) compared to the other HII regions! So let us plot the error as a function of O abundance:



Note that the polynomial fit curve shows an exaggerated wiggle, which we should not take seriously! Emmanuelle's 40000K model (at 12+log(O/H) = 8.63) is quite low, although its oxygen abundance is not that high.

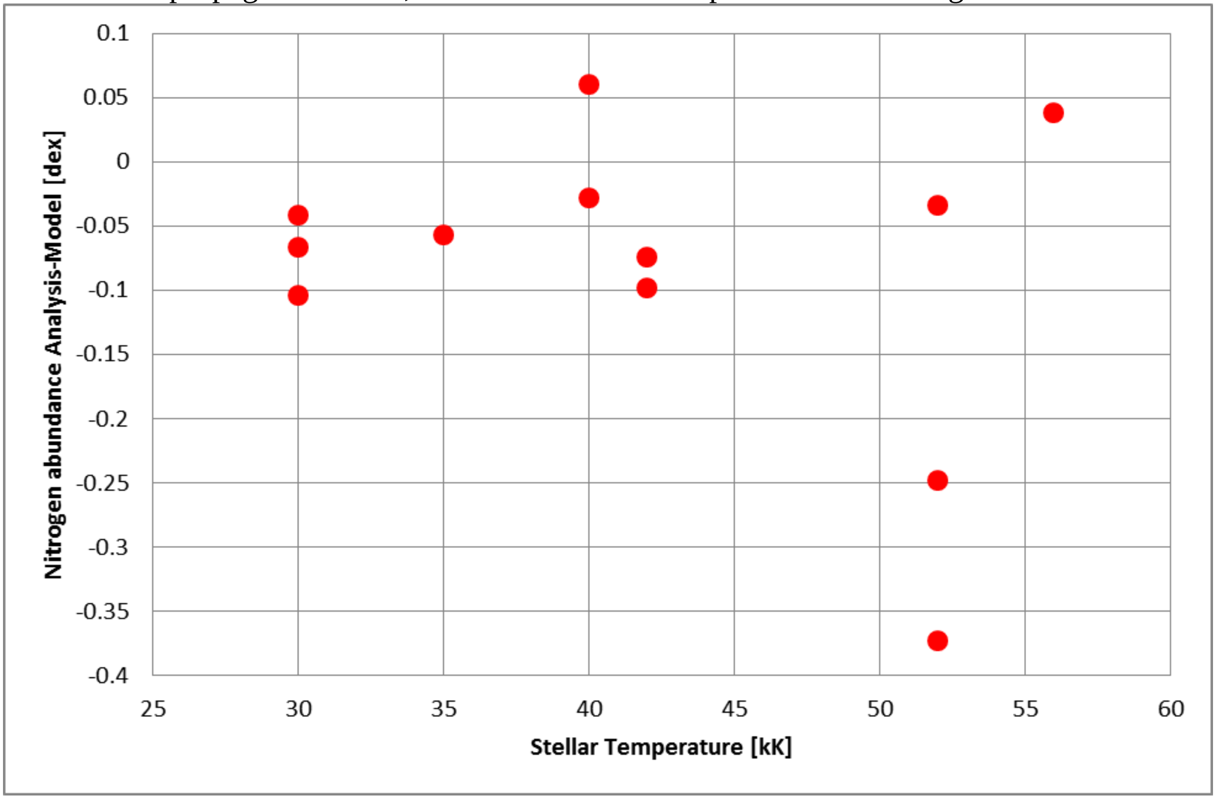
One could expect that the error increases with oxygen abundance, because of the internal physics of the ionized gas: the gas is heated by the UV photons from the central star, but it is cooled by the radiation in the emission spectrum. The electron temperature is the result of the equilibrium of heating and cooling. A more metal-rich gas can cool more efficiently, and thus will have a lower temperature. In the theoretical models, one gets strong gradients of the electron temperature, which means that the temperature that we measure with the 5007/4363 line ratio is no longer a representative value for the average temperature in the ionized nebula … and so we make systematic errors in the abundances derived with our simple method! One would have noticed that the value of the electron temperatures comes down to 5000 K:



But if we consider the other HII regions of low and middle metallicity, the error of the O abundances is **less than 0.1 dex** (better than 25 percent)!

Nitrogen:

To get the nitrogen abundance, we should sum up over all stages of ionization. But in the visible range, only [N II] is present. Because our method corrects for the volume taken up by the other ions by using the fact that wherever oxygen is singly ionized, so is nitrogen, this error in O/H propagates to N/H, and one sees a similar pattern of the nitrogen error:

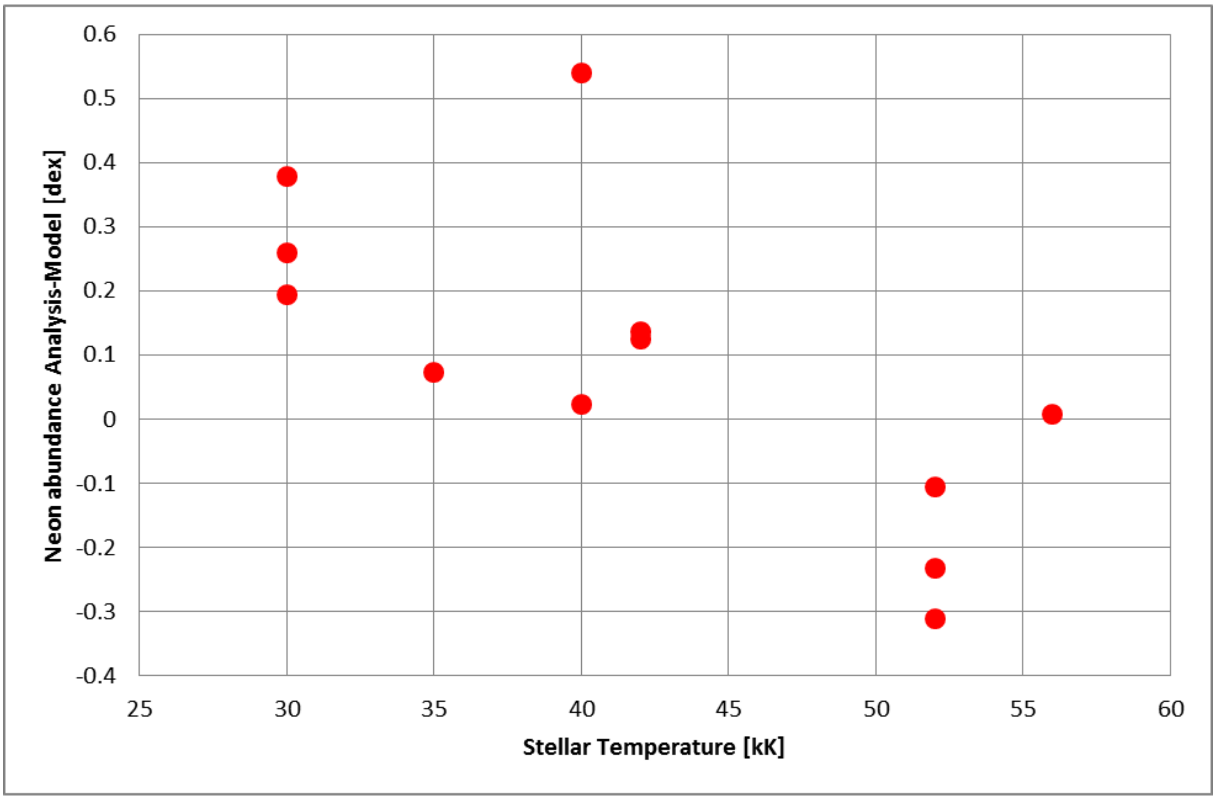


Of course, two of the three high-metallicity objects also misbehave …

But for most HII regions the N abundances seem to be systematically underestimated (by about 0.05 dex) and their dispersion is **still within 0.1 dex** (25 percent)!

Neon:

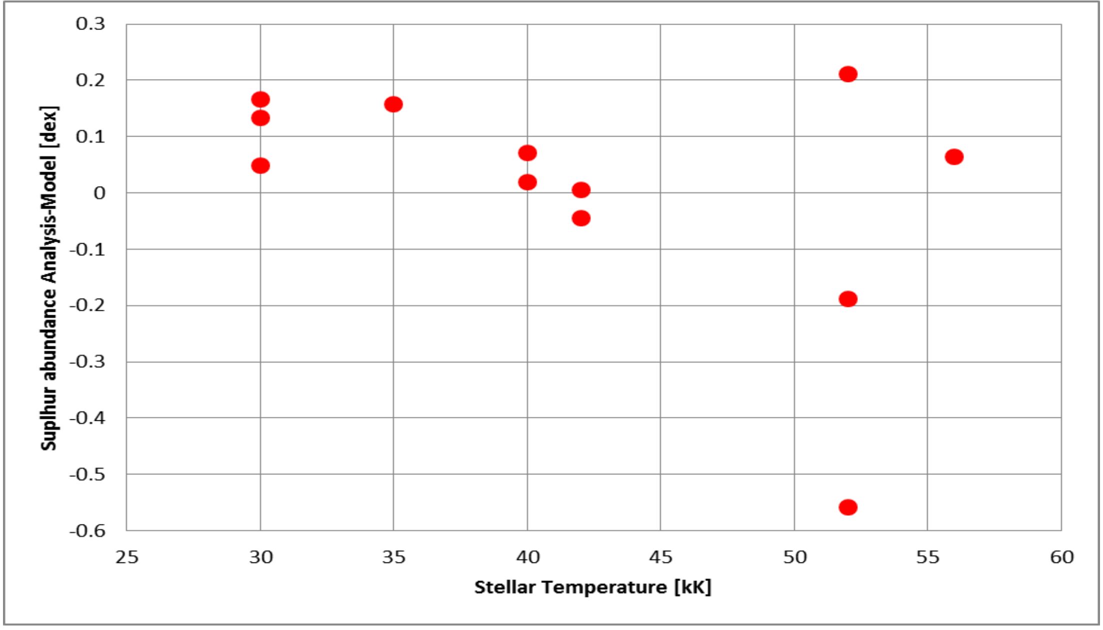
The errors on the neon abundance are quite large, and we only see a weak trend that the errors tend to be smaller in HII region around hotter stars (but the three oddballs give also a very low neon abundance). Other objects also give large deviations: The 30000K models and Simon's 40000K overestimate strongly the Neon abundance, but there seems nothing special about them …



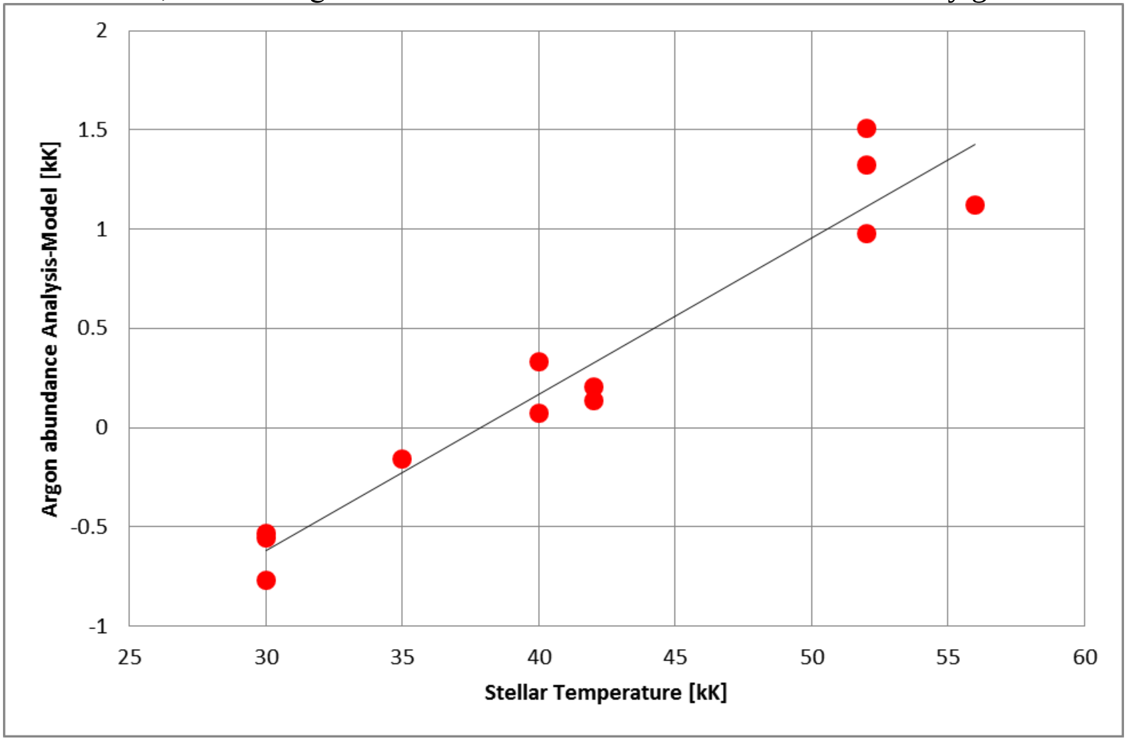
The reason lies with the coexistence of doubly ionized oxygen – seen as [O III] – and neon [Ne III]. This is used to estimate the portion of the nebula where the other neon ions reside, which do not have lines in the optical range. This correspondence is only quite accurate in nebulae around hotter stars. Thus the errors become especially large at low stellar temperatures.

Sulphur and Argon:

Things are worse with S: there is no simple formula to link the ionization of this element – observable in [S II] and [S III] – to another element. In our analysis method we use a certain formula, but it isn't generally valid … so the errors are large. Simon's 52000K object underestimates grossly the sulphur abundance.



With argon, we see rather clear trend of the error with stellar temperature. The reason lies with our observations having only the [Ar III] lines, thus our analysis method has to correct for the other, unseen stages of ionization … but this correction is not really good.



Summary: the elements heavier than oxygen may show rather large errors, partially because there are difficulties of estimating the unseen ions of those elements.

Dependence on electron density:

You noticed that the assumption of the electron density does not make any difference, as long as this value is low. The reason is very simple:

- the intensity ratio of a collisionally excited line and Hβ is given by the ratio of the emissivities, which in turn depends on the abundance ratio, for example:

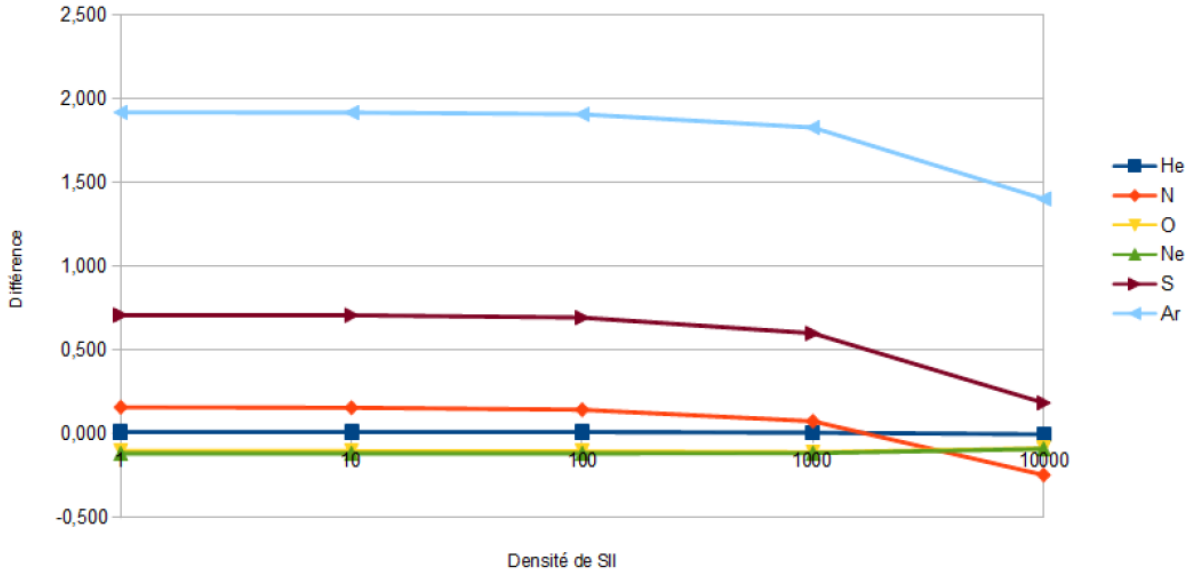
  $$\mathbf{I(OIII) / I(H\beta) = j(OIII) / j(H\beta)}$$

- for the recombination line: $\mathbf{j(H\beta) = \ldots\ n(H^{+})\ n_e\ \alpha_{eff}(H\beta)}$
- for the collisionally excited line: $\mathbf{j(OIII) = \ldots\ n_2(O^{++})\ \ A_{21}}$
- in equilibrium the relation of the densities of ground and excited state in the O++ ion is $\mathbf{n_1\ C_{12} = n_2\,(A_{21} + C_{21})}$ with the rates $\mathbf{C_{ik}}$ for collisions with electrons. This gives $\mathbf{n_2/n_1 = C_{12} / (A_{21} + C_{21})}$
- since we have $\mathbf{C_{12} = C_{21}\ e^{-E/kT}}$ and $\mathbf{C_{21} = \ldots\ \Omega * n_e}$ we get the general expression for the emissivity:

  $$\mathbf{j(OIII) = \ldots\ n_1(O^{++})\ C_{21}\ e^{-E/kT} / (A_{21} + C_{21})}$$
  $$\mathbf{= \ldots\ n_1(O^{++})\ \ n_e\ \Omega\ e^{-E/kT} / (A_{21} +\ \ n_e\ \Omega)}$$

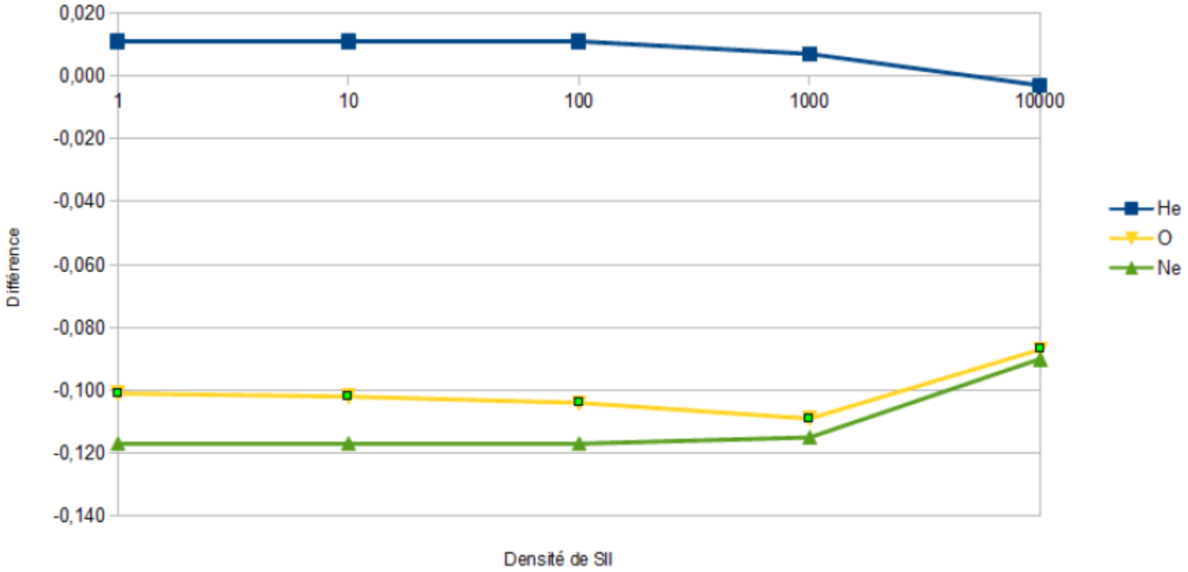
  there are two extreme cases:
- at low densities $\mathbf{j(OIII) = \ldots\ n_1(O^{++})\ \ n_e\ \Omega\ e^{-E/kT} / A_{21}}$ and therefore the emissivity ratio $\mathbf{j(OIII) / j(H\beta)}$ is independent of electron density. As a consequence, the abundance derived from the line intensity does not depend on the actual density
- at high densities the emissivity $\mathbf{j(OIII) = \ldots\ n_1(O^{++})\ \ C_{21}\ e^{-E/kT} / C_{21} = \ldots}$ $\mathbf{n_1(O^{++})\ e^{-E/kT}}$ is independent of density. Thus, $\mathbf{j(OIII) / j(H\beta)}$ decreases with electron density, and we need a larger oxygen abundance to match a given intensity. This effect occurs for the optical lines in our spectra at about densities around 10000 electrons/cm^3 …

Below is a plot from Orianne which shows the effects quite clearly:



Note that because the density is varied over several orders of magnitudes, it is better to plot it with logarithmically spaced values! If we vary the density in a linear fashion, we would see only the decrease at high densities!

He, O, and Ne show only a small variation:



- The HeI lines have a small contribution from collisional excitation, so the higher density results in a higher helium emissivity, and hence we need a lower He abundance to explain the observed lines.
- The [OII] lines are sensitive to collisional de-excitation. This results in an increase of the deduced oxygen abundance for high densities, since the emissivity of the [OII] lines is decreased. Although this is only a small effect on O/H, it has further consequences: the neon abundance is corrected for unseen ions via oxygen, and we see its corresponding increase. Since the ions N+ and O+ occupy the same zone, the nitrogen abundance derived from the [NII] lines is scaled via the O+/O++ abundance ratio: N/H = N+/H+ * (O/H)/(O+/H+)
  Thus the increase with density of the O+/H+ ionic abundance results in a decrease of N/H abundance. Because the O+ zone is only a small part of the entire HII region, this produces the rather large effect seen in the first plot!
- Similarly, sulphur and argon abundances are also corrected via the O+/O++ ratio, and thus show similarly strong effects!

So the propagation of effects in the plasma analysis is somewhat complex because of the ionization correction factors...

Dependence on weak lines:

There are two effects:

- The weak lines OIII 4363 and NII 5755 are important to derive the electron temperature … which is needed to compute the line emissivity. If such a line is not present in the spectrum, the applet will use a standard value of T_e = 10000 K. Depending on whether the real electron temperature is below or above that value, the derived abundances will differ from the value of the full analysis.
- The other issue are the correction factors for unseen stages of ionization. While both oxygen ions O+ and O++ have visible lines in HII regions, only N+ is visible. Luckily, O+ and N+ occupy the same volume in such a nebula, and therefore one can use the O++/O+ ratio to estimate the amount of invisible N++ ions. But this implies that the nitrogen abundance will be influenced by the oxygen lines.
- Likewise, the other elements are also corrected in a similar manner. Thus, the results from the oxygen lines also affect the other abundances. For some elements this works well, but for sulphur and argon, there is no simple and generally valid formula …

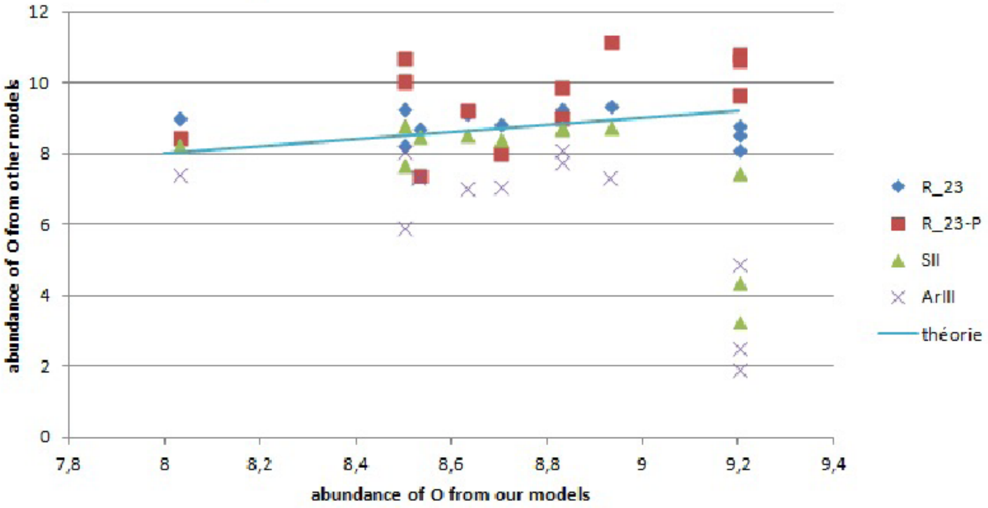
Effects of the [OIII] 4363 and [NII] 5755 lines:

These lines are crucial to measure the electron temperatures:

- [OIII] measures the temperature in the O^{++} zone, which is used to compute the emissivity of all ions present in that zone: He^{+}, O^{++}, Ne^{++}, and Ar^{++}
- [NII] does the same for the N+ zone, where also O^{+}, S^{+}, S^{++} are present
- This is why you have seen that these lines affect only certain elements in certain ways
- While sulphur lines are emitted only from the O^{+} zone, the S abundance is corrected by using the O^{++}/O^{+} ratio, which in turn is affected by both electron temperatures …
- However, the He abundance is not much affected, because it comes from the recombination lines whose emissivity depends only weakly on temperature

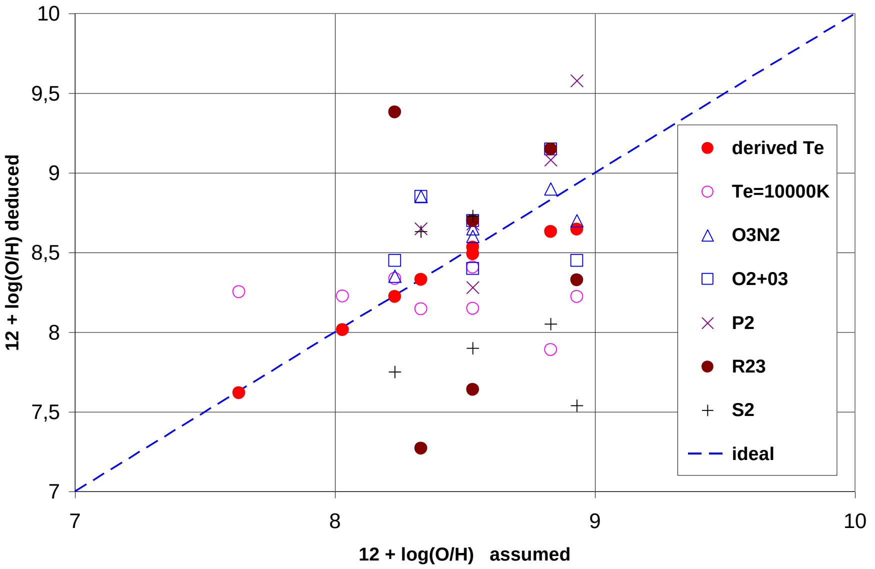
Comparison with Strong Line methods:

You have noticed that the various strong line methods give all sorts of values. There seems to be no single method that works well for all our spectra. Here is the plot of all data from Emmanuelle:



The deviations from the expected values (blue straight line) are enormous: 1 or 2 dex means factors of 10 and 100! The R23 method seems to work a bit better. The ArIII method tends to underestimate the oxygen abundance substantially. Quite surprisingly, the SIII method works quite well, although you had used the 6312 line but with the formula derived for the 9069 line (which is about 20 times stronger)!

Below I show results for various methods, from another year: Assumption of a constant electron temperature of 10000 K gives – quite by chance – nearly constant values around 8.2, and is a complete failure! Some of the strong line methods give abundances which are around the assumed values, they tend to reproduce the variation of the abundances, but some of them are really awful. I trust your calculations which I did not check line-by-line … but it is apparent that strong line methods are quite problematic!



One reason could well be that these methods were designed for HII regions with "realistic" abundance patterns, while for our model spectra I simply changed the abundances arbitrarily! But this means that in HII regions with strange abundances one might get telephone numbers!