Highlights of Astronomy, Vol. 12
International Astronomical Union, 2002
H. Rickman, ed.

NLTE Effects on Oxygen Lines

Dan Kiselman

The Swedish Royal Academy of Sciences, Stockholm Observatory, SE-133 36 Saltsjöbaden, Sweden

Abstract. The NLTE effects affecting oxygen-abundance determinations of solar-type stars are discussed. LTE is safe for the forbidden lines. The permitted triplet at 777 nm is expected to show NLTE effects so that assuming LTE overestimates the abundance, but the magnitude of the effects is dependent on the poorly known cross sections of collisional excitation by collisions with neutral hydrogen atoms. Little is known about the NLTE effects on molecular line formation.

1. Introduction

NLTE effects are the errors introduced by the common approximation of local thermodynamic equilibrium (LTE). Here, NLTE effects on lines used for oxygen-abundance determinations in unevolved or moderately evolved stars of approximately solar effective temperatures will be discussed. The discussion only concerns departures from LTE and disregards all other relevant uncertainties.

2. Atomic lines

Typical NLTE calculations show the forbidden oxygen lines at 630 nm and 636 nm to be formed exceedingly close to LTE. These transitions originate from the O I ground term and their rates are overwhelmingly dominated by collisions. Thus there are no departures from LTE in the line opacity, nor in the line source function.

The O I triplet lines at 777 nm are known to be subject to NLTE effects in early stars. For solar-type stars, the picture is a bit more unclear since quantitative predictions have had problems when confronted with solar observations. Other permitted lines are weaker and less useful than the triplet at lower abundances. Their departures from LTE are similar in mechanism but smaller than those of the triplet.

The typical NLTE treatment of O I in a solar photospheric model shows that the triplet line opacity is close to its LTE value. The line source function $S_{\rm L}$ dips below the Planckian, making the line stronger than in LTE, because of photon losses and scattering in the line. The behaviour is like the two-level atom without continuum (e.g. Mihalas 1978), $S_{\rm L} = (1-\varepsilon)\bar{J}_\nu + \varepsilon B_\nu(T)$, where ε measures the destruction probability of line photons by collisional deexcitation. The effect grows stronger with increased abundance as the line strength increases. But it does not go to zero at low abundance since $J_\nu < B_\nu(T)$ in the IR continuum.

https://doi.org/10.1017/S153929960001399X Published online by Cambridge University Press

The NLTE abundance corrections, $\Delta\epsilon_{\rm O}^{NLTE} = \epsilon_{\rm O}^{NLTE} - \epsilon_{\rm O}^{LTE}$, will *always be negative*, so that an LTE analysis overestimates the abundance. For solar-type stars, $\Delta\epsilon_{\rm O}^{NLTE}$ ranges from 0 to -0.5 dex (e.g., Kiselman 1991; Takeda 1994), getting more significant with increased $T_{\rm eff}$ and decreased $\lg g$. No strong dependence on [Fe/H] has been predicted that would seriously change the slopes in [O/Fe] plots. At higher $T_{\rm eff}$'s, there will be a significant departure from LTE of the line opacity so that the results will depend on details of the atomic model outside the line studied.

Support for the NLTE modelling comes from the centre-to-limb (μ) behaviour of the triplet in the Sun which is inconsistent with LTE (Altrock 1968; Sedlmayr 1974). NLTE line strengths are, however, too large for the $\epsilon_{\rm O}^{NLTE} \approx 8.9$, based on other lines, that for a long time was the standard solar value (Sneden et al. 1979; Kiselman 1991, 1993). Granulation and 3D NLTE effects do not solve the discrepancy (Kiselman & Nordlund 1995). Allowing solar $\epsilon_{\rm O}$ below 8.9 (e.g., Reetz 1999) probably will, but the problem of uncertain collisional cross sections has to be solved for certainty.

Collisional excitations by atoms in cool-star NLTE work were introduced by Steenbock & Holweger (1984), who generalised the estimates of Drawin (1968, 1969) to inelastic collisions between hydrogen atoms and other species (see also Lambert 1993). Many authors have tried to get better estimates by multiplying these rates with a factor x determined by empirical fitting. Tomkin et al. (1992) fitted the triplet lines to the solar spectrum assuming $\epsilon_{\rm O} = 8.92$, resulting in large collisional rates almost producing LTE. Takeda (1995) found $x = 1.0$ from a multiparameter fit of solar line profiles. King & Boesgaard (1995) confirmed the inconsistency of the solar μ dependence with LTE. Reetz (1998, 1999) used the μ dependence and solar line profiles to find H I collisions negligible ($x = 0.0$). The same result came from minimising the abundance spread for the individual triplet lines for stars of different $T_{\rm eff}$. Gratton et al. (1999) found that $x = 3.2$ gave consistent abundances for different oxygen lines in RR Lyræ stars.

These empirical attempts are apparently very model dependent. If one discards the extrasolar evidence and that relying on certain values of the solar $\epsilon_{\rm O}$, it seems that the solar centre-to-limb behaviour is still a rather strong argument that hydrogen collisions are not very significant and that they definitely cannot induce LTE. Circumstantial support for this comes from detailed calculations of the H I excitation cross sections of the Na D lines (Belyayev et al. 1999) which are $10^{-2} - 10^{-4}$ of the Drawin-style prediction. See also Caccin et al. (1993).

In the time since the Kiel group pointed out inelastic collisions with hydrogen atoms as potentially very important in cool-star NLTE work, many large and expensive telescopes and spectrographs have gone from visionary ideas to first light. But our knowledge about these collisional rates – so important for interpreting the results of these technological wonders – has not advanced much.

3. Molecular lines

Hinkle & Lambert (1975) expect Boltzmann equilibrium to hold at solar temperatures among vib-rot levels in the electronic ground state of diatomic molecules like CO and OH, but possible departures from LTE in line source functions of electronic transitions. For weak UV lines (OH in metal-poor stars) this could lead to LTE abundances being underestimates. Departures from LTE in the chemical equilibrium could be driven by photodissociation. Even statistical equilibrium may not be reached in the few minutes the upwelling gas in a granule spends around the photosphere (Uitenbroek 2000). If so, all modelling assuming statistical equilibrium will derive too low abundances.

4. Conclusions

NLTE effects can be safely disregarded for the forbidden oxygen lines, while the situation for molecular lines is unclear.

The 777 nm triplet lines are not formed in LTE though NLTE effects will not change the slopes in the [O/Fe]–[Fe/H] diagrams very much – certainly increase the error bars because of the uncertainties in the collisional cross sections. LTE always leads to overestimated abundances, and so LTE results define an *extreme* on the possible range of abundances, not a conservative mean hypothesis.

Acknowledgments. Dr. M. Asplund is thanked for rewarding discussions.

References

Altrock, R. C. 1968, Solar Phys., 5, 260

Belyayev, A., Grosser, J., J., H., & Menzel, T. 1999, Phys.Rev.A, 60, 2151

Caccin, B., Gomez, M. T., & Severino, G. 1993, A&A, 276, 219

Drawin, H.-W. 1968, Z. Phys., 211, 404

Drawin, H.-W. 1969, Z. Phys., 225, 483

Gratton, R. G., Carretta, E., Eriksson, K., & Gustafsson, B. 1999, A&A, 350, 955

Hinkle, K. H. & Lambert, D. L. 1975, MNRAS, 170, 447

King, J. R. & Boesgaard, A. M. 1995, AJ, 109, 383

Kiselman, D. 1991, A&A, 245, L9

Kiselman, D. 1993, A&A, 275, 269

Kiselman, D. & Nordlund, Å. 1995, A&A, 302, 578

Lambert, D. L. 1993, Phys. Scr., T47, 186

Mihalas, D. 1978, "Stellar atmospheres", 2nd ed., (San Francisco: Freeman)

Reetz, J. 1998, "Sauerstoff in kühlen Sternen und die chemische Entwicklung der Galaxis", Ph.D. thesis, Ludwig-Maximilians-Universität, Munich

Reetz, J. 1999, Ap&SS, 265, 171

Sedlmayr, E. 1974, A&A, 31, 23

Sneden, C., Lambert, D. L., & Whitaker, R. W. 1979, ApJ, 234, 964

Steenbock, W. & Holweger, H. 1984, A&A, 130, 319

Takeda, Y. 1994, PASJ, 46, 53

Takeda, Y. 1995, PASJ, 47, 463

Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, AJ, 104, 1568

Uitenbroek, H. 2000, ApJ, 536, 481