Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©*2004 IAU*
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Statistical equilibrium of O and CO in disks around young A stars

Inga Kamp and Gerd-Jan van Zadelhoff

Leiden Observatory, PO Box 9513, 2300 RA Leiden, The Netherlands

Abstract. The frequently made assumption that gas and dust temperatures are equal cannot be applied to the low density disks (10^4 cm^{-3} $< n_{tot} <$ 10^8 cm^{-3}) around young A stars ("Vega-type" stars), because the collisional coupling is too weak. It turns out that OI fine structure lines and CO rotational lines are two very important cooling terms in the heating/cooling balance for the gas. Their level population numbers are far from LTE and depend strongly on the background radiation field, given by the thermal dust emission of the disk and the cosmic microwave background.

1. Introduction

About 20% of the nearby A dwarfs are surrounded by dust disks. These stars are often referred to as "Vega-type" stars. Kamp & Bertoldi (2000) tried for the first time to model the dust and gas component for these disks consistently, so far assuming $T_{\rm gas} = T_{\rm dust}$.

But, for the modelling of emission lines and hence the interpretation of ISO spectra, the gas temperature is one of the most important input parameters. It can be determined more sophistically from a detailed balance of all relevant heating and cooling processes.

2. The model

The basic model is described by Kamp & Bertoldi (2000) and here only a short summary will be given: the thin hydrostatic disk models have masses between 0.05 and 2 $M_\oplus$, the gas-to-dust mass ratio is fixed to $M_{\rm gas}/M_{\rm dust} = 100$. The dust component is composed of spherical black body dust grains with a typical size of $a = 3$ μm. The disks have an inner hole of $R_{\rm i} = 40$ AU and the central stellar UV radiation field $F_{\rm UV}$ is taken from the Kurucz (1992) photospheric models. The gas component is described by a chemical network comprising 47 species and 260 reactions.

3. The gas temperature

Two very important cooling processes are OI fine structure line cooling and CO rotational line cooling (Kamp & van Zadelhoff 2000). It turns out that the approximation of LTE for O and CO is not valid for the parameter space covered

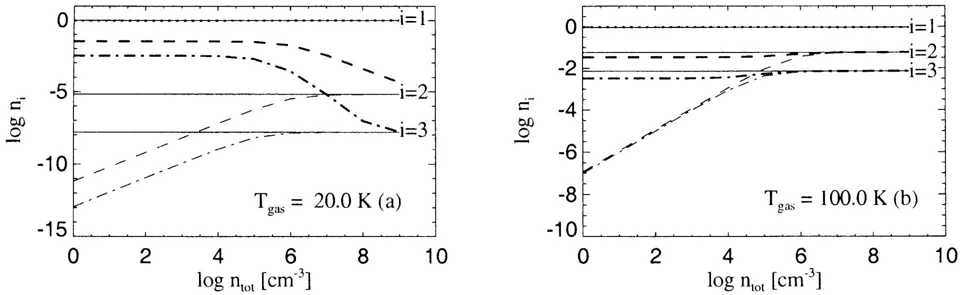

Figure 1. OI fine structure level populations of the ground state for two different gas temperatures (a) 20 K and (b) 100 K as a function of particle density n_{tot}: LTE (solid line, fine structure levels are annotated), NLTE $i = 1$ ($3P_2$, dotted line), $i = 2$ ($3P_1$, dashed line), $i = 3$ ($3P_0$, dash-dotted line). The thin lines present the result without P_ν, the thick lines with P_ν

by the above described disk models. Hence, detailed statistical equilibrium calculations are carried out in order to derive accurate cooling rates.

3.1. Statistical equilibrium of oxygen

The oxygen model atom consists of the three fine structure levels of the OI ground state, spontaneous and stimulated emission, IR background absorption and collisions with H_2, H and electrons.

The IR background radiation field P_ν is assumed to be the sum of the thermal dust emission $P_{\nu,\mathrm{dust}}$ and the cosmic microwave background, $B_\nu(2.7\ \mathrm{K})$. As a first step, the local approximation for the dust emission is implemented: $P_{\nu,\mathrm{dust}} = B_\nu(T_{\mathrm{dust}})$. To illustrate the basic physics, the dust temperature is fixed to a typical value of 80 K.

Fig. 1 illustrates the following conclusions. In the parameter range of the disk models presented here, LTE is a good approximation for densities larger than $10^7\ \mathrm{cm}^{-3}$. The IR background plays an important rôle, because the level population numbers adjust to the "temperature" of the background radiation field. This leads for low gas temperatures to a strong overpopulation with respect to LTE, while for $T_{\mathrm{gas}} > T_{\mathrm{dust}}$ the levels are depopulated with respect to LTE.

3.2. Statistical equilibrium of CO

The CO model molecule consists of the first 26 rotational levels of the vibrational ground state $v = 0$. The same approach as for the OI model atom is followed.

The basic results for CO are illustrated in Fig. 2. LTE is only a good approximation for densities larger than $10^8\ \mathrm{cm}^{-3}$. For low densities $n_{\mathrm{tot}} \lesssim 10^4\ \mathrm{cm}^{-3}$ the level population numbers adjust to the "temperature" of the IR background radiation field P_ν while for larger densities collisions dominate the statistical equilibrium and the population numbers tend towards LTE.

https://doi.org/10.1017/S0074180900218202 Published online by Cambridge University Press

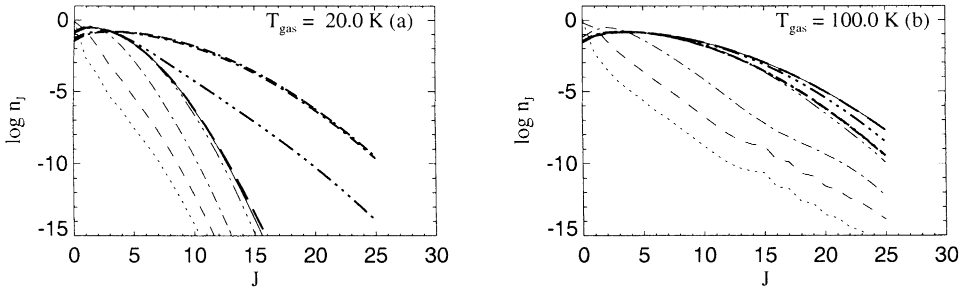

Figure 2. CO level population numbers for $v = 0$, $J = 0 \ldots 25$ for two different gas temperatures (a) 20 K and (b) 100 K: LTE (solid line), NLTE at $n_{\rm tot} = 1$ cm^{-3} (dotted line), at 10^2 cm^{-3} (dashed line), at 10^4 cm^{-3} (dash-dotted line), at 10^6 cm^{-3} (dash-three-dotted line), and at 10^8 cm^{-3} (long-dashed line). The thin lines present the result without P_ν, the thick lines with P_ν

4. Discussion

The level population numbers for oxygen and carbon monoxide are not in LTE throughout the parameter space of the disk models presented here. Infrared pumping of the levels is very important for densities below 10^4 cm^{-3}. In these low density regions the level population numbers adjust simply to the background radiation field P_ν composed of the thermal dust emission from the disk and the cosmic microwave background. The local approximation implemented here for the thermal dust emission does not hold for the typically optically thin disk models. The "real" radiation field will be weaker than $B_\nu(T_{\rm dust})$ and hence the above described effect less pronounced.

Hence, via P_ν the dust temperature will still influence the gas temperature in these disks, even if collisions are totally inefficient in coupling these two.

Acknowledgments. The authors thank Ewine van Dishoeck for numerous helpful discussions and I.K. acknowledges support by the "European Commission" under grant MCFI-1999-00734.

References

Dent, W.R.F., Greaves, J.S., Mannings, V., Coulson, I.M., Walther, D.M. 1995, MNRAS, 277, L25

Kamp, I., Bertoldi, F. 2000, A&A, 353, 276

Kamp, I., van Zadelhoff, G.-J. 2000, A&A, submitted

Kurucz, R.L. 1992, Rev. Mex. Astron. Astrofis., 23, 181

Liseau, R., Artymowicz, P. 1998, A&A, 334, 935

Savoldini, M., Galetta, G. 1994, A&A, 285, 467

Yamashita, T., Handa, T., Omodaka, T. et al. 1993, ApJ, 402, L65

Zuckerman, B., Forveille, T., Kastner, J.H. 1995, Nature, 373, 494