The Evolving ISM in the Milky Way & Nearby Galaxies

Probing Atomic and Molecular Gas in Proto-planetary Disks

R. Meijerink[1], D.R. Poelman[2], A.E. Glassgold[1], J.R. Najita[3], A.G.G.M. Tielens[4,5],
M. Spaans[5]

ABSTRACT

Besides being a reservoir of accreting material onto a newly formed star, the study of circumstellar disks not only shed light on the formation mechanisms of stars, but also on the formation process of planets. We discuss the expected characteristics of line emission produced in atomic and molecular gas of X-ray irradiated disks and discuss possible observables for SOFIA and Herschel.

Subject headings: accretion, accretion disks – infrared: stars – planetary systems: proto-planetary disks – stars: formation: pre-main sequence – X-rays: stars – radiative transfer

1. Introduction

Disks play a crucial role in planet and star formation. Although most of the disk mass is initially gaseous, observationally little is known about the gas properties. Most of the observations focus on dust properties, such as scattered light images, interferometric measurements and SEDs. X-rays, which are produced by Young Stellar Objects, interact with the upper layers of the surrounding proto-planetary disk and are expected to dominate the thermal and chemical balance. Strong [NeII] 12.81μm is predicted for these disks, consistent with recent Spitzer observations. We also estimate fluxes of complementary diagnostics, such

---

[1] Astronomy Department, University of California, Berkeley, CA 94720, United States

[2] School of Physics & Astronomy, University of St. Andrews, North Haugh, St. Andrews KY16 9SS, Scotland

[3] National Optical Astronomy Observatory, Tucson, AZ 85719, United States

[4] NASA Ames Research Center, MS245-3, Moffet Field, CA 94035, United States

[5] Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands

as atomic forbidden and fine-structure lines of [CI], [CII], [OI], and [SI], and molecular pure rotational and ro-vibrational lines of H_2O.

A special focus will go to identifying H_2O lines that will help to locate the snow-line in disks around T Tauri stars. The snow-line is believed to play an important role in the formation process of planets. Unfortunately, up to now the place of the snow-line has not been determined observationally in proto-planetary disks.

2. Disk model

The excitation of neon and other species depend on temperature, and the densities of electrons and (atomic and molecular) hydrogen. We calculate the chemical and thermal structure for the generic T Tauri disk models of D'Alessio et al. (1999) using an updated version of the code presented by Glassgold et al. (2004). We investigate X-ray luminosities ranging from L_X=10^{29}-10^{31} erg/s. Typically, the temperatures range from $T = 4000$ K at high altitudes to $T = 30 - 200$ K close to the mid-plane, where the gas is thermally coupled to the dust. The electrons originate mainly from hydrogen atoms, which are ionized by fast electrons resulting from X-ray ionization. Note that electron abundances can be as high as x_e=10^{-2}-10^{-1} (see Fig. 1).

3. Line emission

Each line traces a different region of the disk, depending on its critical density and excitation temperature. Lines with high excitation temperatures, such as the [NeII] 12.81μm and [SI] 25.25μm fine-structure line, trace the warm upper layers, since these have high excitation temperatures. The [OI] 63μm is produced all throughout the entire disk, although a large part of the oxygen atoms are locked up in CO, H_2O and O_2 close to the mid-plane (see Fig. 2). Pure rotational lines of H_2O are only produced at large perpendicular column densities. Its ro-vibrational lines are tracing the hot gas very close to the star.

3.1. H_2O rotational transitions

The pure rotational lines of water under consideration have wavelengths between 75 and 1600μm, which are potentially observable by HIFI and PACS on Herschel. It turns out that some of the lines will be observable within a couple of hours when water would not freeze-out, given a sensitivity of $\sim 10^{-14/-15}$ erg cm^{-2} s^{-1} (156-622μm) for a 5σ detection

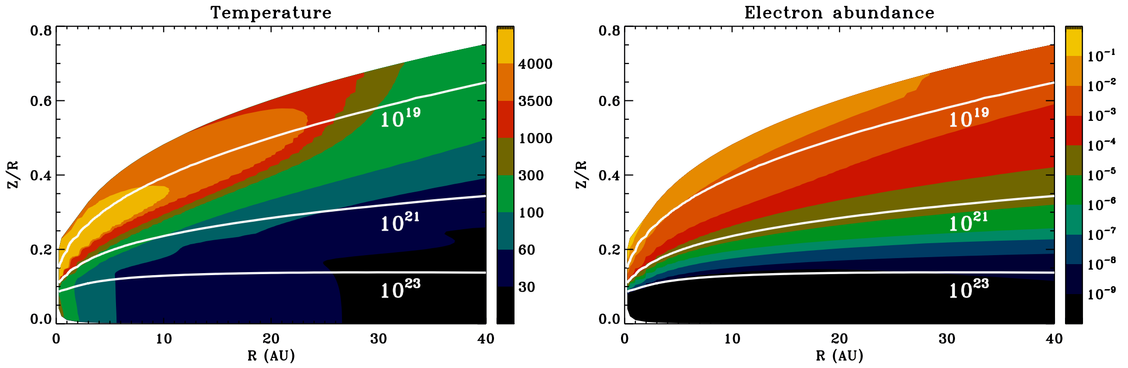

Fig. 1.— Temperature (left) and fractional electron abundance (right). The perpendicular total hydrogen column density N_H is over-plotted in contours.

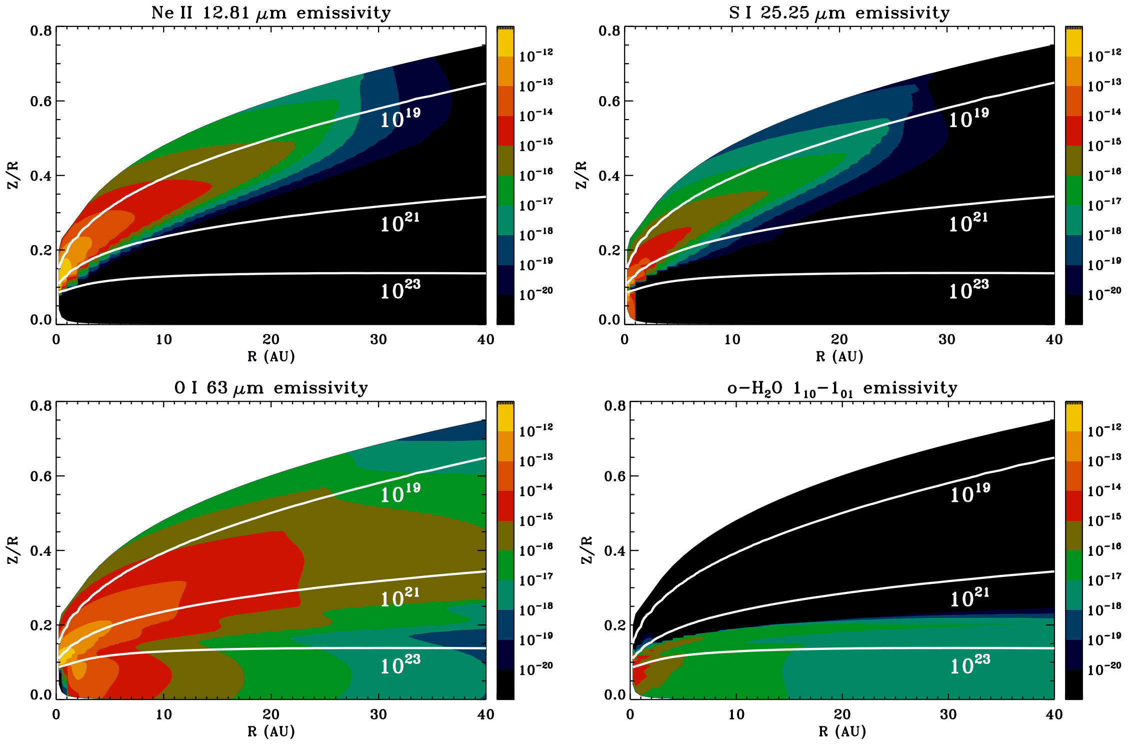

Fig. 2.— Line emissivities throughout the disk with perpendicular column density in contours.

within an hour. However, it is very likely that freeze-out will occur at the large densities and low temperatures where this line emission is produced. To account for this, we have opted to assume a uniform H_2O abundance in the freeze-out zone, i.e., where $T < 110$ K. The effects on the radial profile is plotted in Fig. 3.

3.2. H_2O ro-vibrational transitions

Ro-vibrational transitions around 6μm have been calculated, where we assume the ground vibrational levels to be in the LTE. This is a good approximation since the regions where this emission is produced are very high ($n > 10^9$ cm^{-3}). The 6μm lines are excited due to fluorescence by high energetic photons from the central star.

In general, we find that a large part of the emission originates from small radii, i.e., $R < 0.4$ AU. Hence, effects of freeze-out are noticeable in the estimate of the total flux.

The dust-size distribution in a proto-planetary disk is not necessarily the same as in the ISM. Therefore, we mimic dust growth by reducing the dust opacity up to a factor of 1000. Besides this, we investigate the influence of different freeze-out temperatures (110, 145, and 170 K) on the received flux and line profiles. We find that fluorescent emission is more extended (up to 5 AU) and more important than collisional excitation for lower dust opacities, with fluxes up to 100 times higher.

Note that in the high spectral resolution mode, EXES is able to resolve the effects on the line shape when water freezes-out at a particular distance from the star, which is shown in Fig. 4.

4. Conclusion & Outlook

We have constructed models to study the excitation of gas in atomic and molecular regions of proto-planetary disks. In this, numerical simulations that produce the thermal and chemical structure of X-ray irradiated disks are combined with radiative transfer tools. We find that:

1. The neon and X-ray luminosities show a correlation (Meijerink et al. 2008, in press). The neon fluxes are consistent with Spitzer observations (Pascucci et al. 2007; Lahuis et al. 2007), but more complex modeling is required.
2. Other lines also show a correlation with X-ray luminosity. Lines tracing the warmest

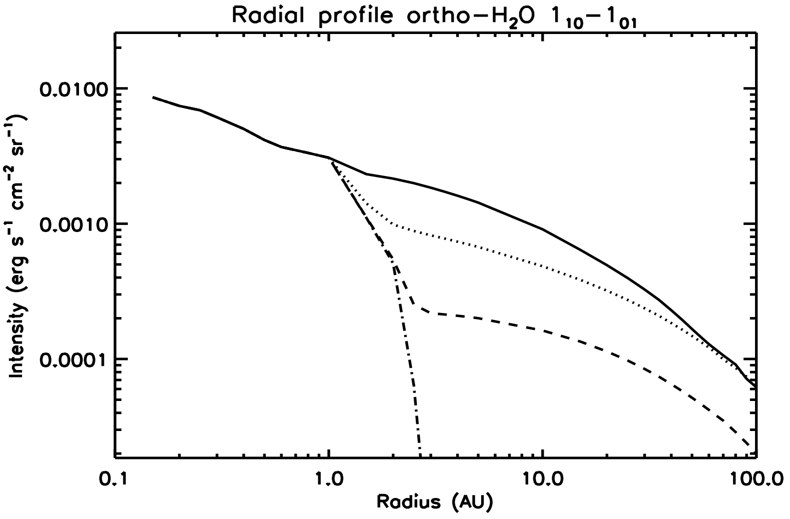

Fig. 3.— Radial profile of the ortho-H_2O 1_{10}-1_{01} line without (solid line), and with freeze-out gas-phase water abundances of 10^{-8} (dotted), 10^{-10} (dashed) and 10^{-15} (dash-dotted).

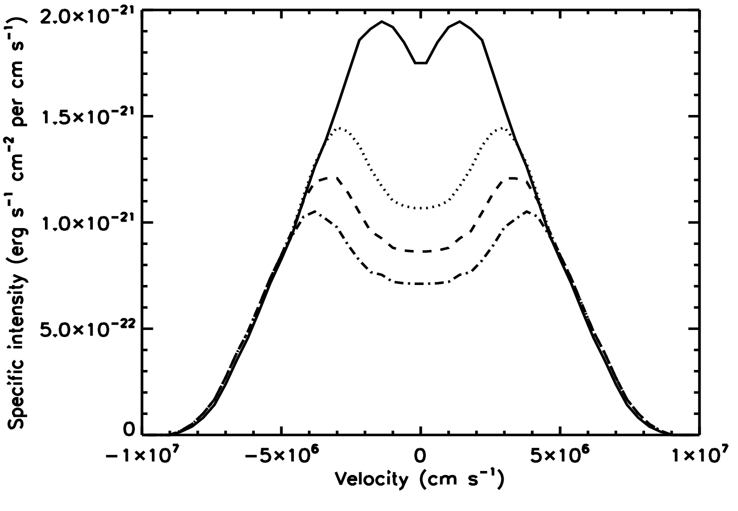

Fig. 4.— Line profile for the $(010)2_{12}$-$(000)1_{01}$ ro-vibrational transition, where the different lines represent no freeze-out (solid line), and freeze-out at 110 K (dotted), 140 K (dashed) and 170 K (dash-dotted), and the dust opacity reduced by 100 with respect to normal ISM conditions.

regions of the disk, such as [OI] 5577Å, show the strongest correlation.

3. The [SI] 25.25μm emission is too weak to be observed with Spitzer or SOFIA. The [OI] 63μm line (observable with Herschel) traces gas deeper into the disk, and is complementary to, e.g., [NeII].
4. We find that the rotational water lines will be marginally detectable when $x(\mathrm{H_2O}) > 10^{-10}$ in the freeze-out zone.
5. Ro-vibrational lines around 6μm are unobservable when fluorescent excitation does not occur.
6. Line ratios around 6μm are not useful as a diagnostic tool to determine the location of the snow-line, but including the 2.3μm might turn out to be very fruitful.
7. The 6μm line profiles change when water freezes-out. We have shown that there is a clear shift in the peak velocities, which is observable within the available velocity resolution of EXES on SOFIA.

RM was supported by NSF grant AST-0507423 and NASA Origins of the Solar System grant NNG06GF88G.

REFERENCES

D'Alessio, P. et al. 1999, ApJ, 527, 893

Glassgold, A. E. et al. 2004, ApJ, 615, 972

Lahuis, F. et al., 2007, ApJ, 665, 492

Meijerink et al. 2008, ApJ, in press, arXiv:0712.0112v1

Pascucci et al. 2007, ApJ, 663, 383

This preprint was prepared with the AAS LaTeX macros v5.0.