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EXPLORING THE GAS CONSTITUENTS IN DEBRIS DISKS WITH HIGH RESOLUTION UV SPECTROSCOPY

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Abstract. We can learn about the composition, the structure and the physical state of the gas in a debris disk from the observations of UV atomic absorption features in the UV spectrum of a hot star when the disk is oriented nearly edge-on to our line of sight. This is illustrated by our analysis of 304 absorption features from 25 different species in a total of 108 energy levels in the UV and visible spectra of 51 Oph. We interpret the relative populations of atoms in excited fine-structure and metastable levels in terms of optical pumping and collisional interactions by electrons in the disk. In the case of 51 Oph we conclude that most of the gas that we can detect is situated at about 6 AU from the star, with an electron density of $[10^5 - 3\,10^6]$ cm^{-3} and a temperature T = 8000 K. The gas has N(H I) = 10^{21} cm^{-2}, it is partly ionized and, except for a deficiency of carbon, has an element composition similar to that of a mildly depleted ISM or the solid material within Jupiter-class comets. We will also mention the analysis of a few other disk spectra.

Keywords: Circumstellar gas, Circumstellar matter, Circumstellar disks, Abundance ratios, Debris disks

1 Introduction

Images of thermal emission by dust recorded by ALMA reveal complex morphologies which guide us in our interpretations of dynamical influences within debris disks, including interactions with planets. With few exceptions these studies have mapped the circumstellar domain only beyond about 20 AU from the star (see, e.g., a review by Hughes et al., 2018).

Closer to the star there is mostly atomic gas, which can be revealed by absorption features in the stellar spectrum that appear at visible and UV wavelengths for those systems that are nearly edge-on to the line of sight. In the visible part of the spectrum features from the ground states of Ca II and Na I signal the existence of circumstellar absorptions and some of the kinematic behavior of the gas, but they are hard to interpret because they are minor constituents that need ionization corrections and are subject to interference from foreground gas in the interstellar medium. The possibility of seeing circumstellar absorptions of preferred ionization stages in visible spectra is generally very limited, although for a white dwarf star Redfield et al. (2017) were able to detect such features. By contrast, in the ultraviolet there are numerous absorptions from excited fine-structure and metastable levels of atoms (hence no interference from the ISM). These features offer a wealth of information and the purpose of this talk was to accomplish the following:
- Draw attention to the value of doing UV spectroscopy of nearly edge-on disks
- Show that UV spectra of debris disks stars exhibit a rich assortment of lines from many different elements, with hundreds of lines arising from excited populations in metastable levels
- Show that they tell us a lot about atomic gases in the inner portion of the disk and reveal the composition, the structure, the physical state and the origin of the gas in a debris disk.

We illustrate this with the study of 51 Oph, a Herbig B9.6 star, 1.2 Myr old, with a mass of 3.3 M_{sun} and located at a distance of 123 pc. Its high resolution ($\lambda/\Delta\lambda$=114 000), STIS ultraviolet spectrum (1280-2396 Å + 2576-2845 Å) sat in the HST archive together with that of a few other disk stars, and is complemented by spectra in the visible (UVES) and far-UV (FUSE and HUT). This study was published by Jenkins & Gry (2020).

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2 Line identification and profile fitting

In the spectrum of 51 Oph we identified 304 atomic absorption lines from 25 different species present in the disk: C I, C II, N I, O I, Na I, Mg I, Si I, Si II, P I, P II, S I, Cl I, Cl II, Ca I, Ca II, Ti II, Cr II, Mn II, Fe I, Fe II, Co II, Ni II, Cu II, Zn I, Zn II, for which we have measured column densities for a total of 98 different atomic levels (43 different levels of Fe II up to an energy of 36 252 cm^{-1}).

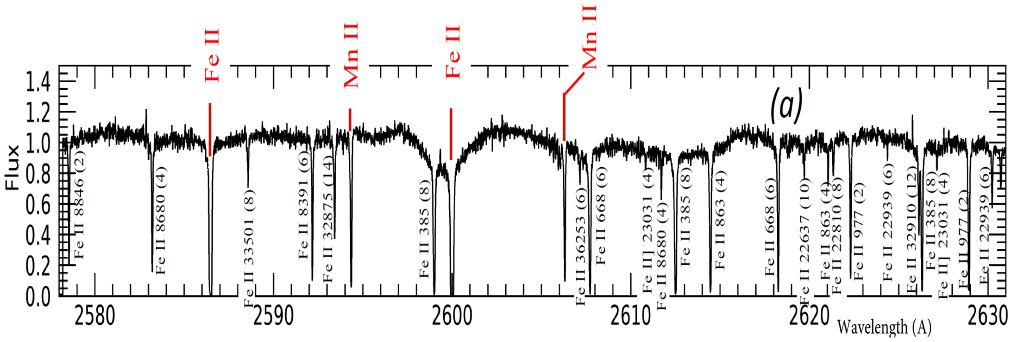

Fig. 1. Example of a portion of the spectrum dominated by lines from Fe II metastable levels. Features identified in red indicate absorptions from the ground states which suffer some contamination from foreground interstellar gas.

All excited lines for all ions can be very well represented with the combination of two components: a strong narrow component, the width of which is consistent with a thermal broadening with T1 = 8000 K and a turbulent broadening $b_{1,turb} = 1.9\,\mathrm{km\,s^{-1}}$, and a weaker broader component,with $b_2 > 6.5\ \mathrm{km\,s^{-1}}$ (thermal and turbulent broadening), slightly displaced in velocity ($\Delta V = -1.6$ km s^{-1}). For neutral atoms (Fig. 2 right panels), we only detect the strong narrow component. For any absorption out of an atom's electronic ground state (like Si II, Fig. 2 upper left panel), there is an additional contribution from the foreground ISM.

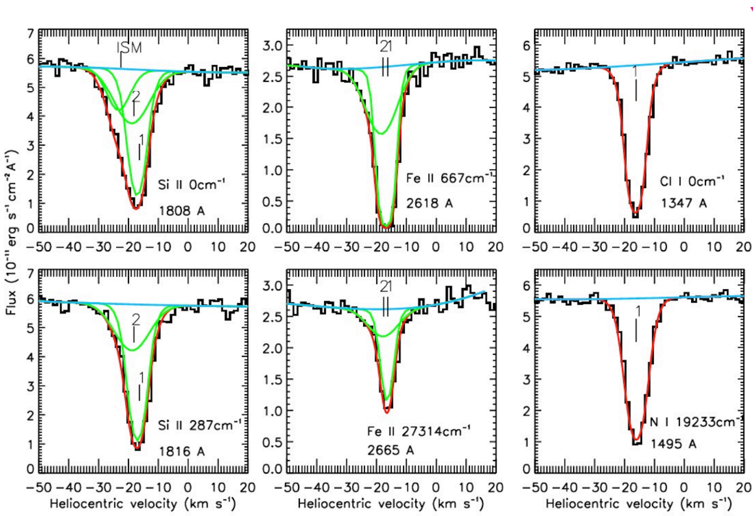

Fig. 2. Example of fitted absorption line profiles from gas in the disk around 51 Oph. The profile fitting has been performed with Owens. Black: observations, red: best fits, green: fits to the two individual components, blue: stellar continuum.

3 Disk orientation

Two considerations suggest that the disk is not seen exactly edge-on: 1- Absence of CO and H2 in absorption, in contrast with CO seen in emission in the IR very close to the star (e.g. Tatulli et al 2008). Hence the sight-line does not sample the central plane of the disk where molecules are shielded from dissociating radiation. 2- Presence of emission at the bottom of saturated O I fine-structure lines. We interpret this as star light being resonantly scattered by oxygen atoms in the far side of the disk, which thereby bypass foreground absorption (Fig. 3).

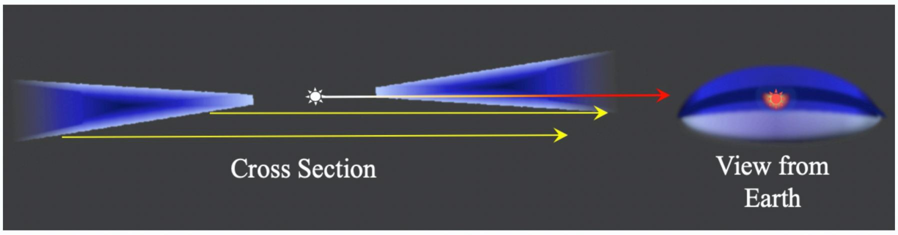

Fig. 3. A schematic illustration of a disk inclination that can create the emission that is superposed on the cores of the absorption lines of excited O I, photons reaching the disk far side being resonantly scattered within the OI features.

4 Boltzmann plots for metastable levels of N I, Fe II and Ni II

The metastable levels are populated by a combination of inelastic collisions with electrons and optical pumping by the light of the star. We derived the corresponding equilibrium equations (starlight excitations, spontaneous radiative decays, stimulated emission, and upward and downward collisions with electrons and hydrogen atoms) and then modeled the stellar flux and attenuation with distance. After we obtained the relevant atomic data for N I, Fe II, Ni II that consisted of the various rates for radiative transitions and collisional excitation and de-excitation, we explored how well our observations agreed with the equilibrium calculations for various combinations of electronic density n(e), distance from the star R and temperature T (Fig. 4 left).

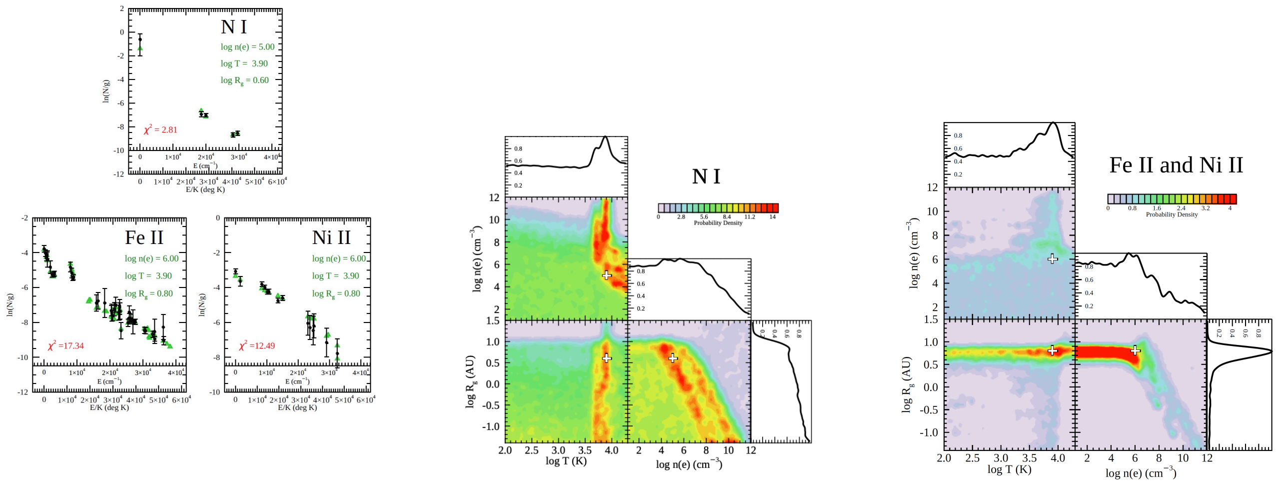

Fig. 4. Left: Boltzmann plots ln(N/g) vs. energy for metastable levels of N I, Fe II and Ni II. Black: observations, green: calculated values for the specified parameters. **Right:** Outputs from the MCMC analyses that indicate the relative probabilities of the fundamental parameters that govern the populations of the excited levels of N I, Fe II and Ni II.

4.1 Comprehensive study of the excited level populations for Fe II, Ni II and N I.

We use a MCMC analysis to derive the regions of high probabilities in the log n(e), log T and log R (distance to the star) parameter space and show that most of the gas is at R $\simeq$ 6 AU from the star, T $\simeq$ 8000 K, $10^5 < n(e) < 3\,10^6 cm^{-3}$ (Fig. 4 right).

4.2 Abundances

The gas is so excited that in order to derive the column densities we need to take all levels into account, so for each element we sum the contributions from all levels for the preferred ionization stage. Missing levels with no measured lines are estimated from the neighbouring levels on the basis of the most probable model.
From N(O I) and N(N I) we derive the neutral hydrogen column density of N(H I)= 10^{21} cm^{-2}. We note a surprisingly large abundance of Cl I which is explained by charge exchange between Cl $^{+}$and neutral hydrogen. This implies that $n(H_0)$ is also high: $n(H_0) > 3.5\ 10^5\ cm^{-3}$. We compare the abundance pattern shown in Fig. 5 to that of the ISM with several depletion degrees, and also to that of a few solids: dust in the ISM, terrestrial crust, or comets. We find that the abundances in the disk are close to that of a mildly depleted ISM or a Jupiter-class comet. This suggests that the gas may be due to destructive processes of solids in the midplane, in agreement with the presence of Falling Evaporative Bodies. The fact that the preferred distance of the gas is 6 AU may imply that closer to the star there are more collisions, inducing more evaporation.

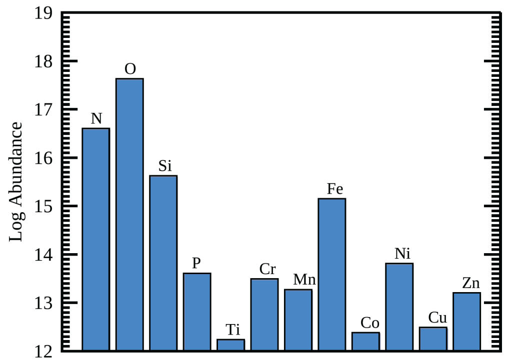

Fig. 5. Total column densities of the preferred ionization states of the elements in the disk of 51 Oph

5 Future potentials

As a conclusion, the high resolution spectra are extremely effective tools for revealing the physical conditions in inner parts of disks, their structure and their kinematics. We think it is important to expand their use for stars other than 51 Oph. We have started to analyze the UV spectra of several other debris disks that exist in the HST archive, some with spectra even richer in number of lines and some showing interesting kinematical features. For instance in the case of HD42111 we have performed –in collaboration with Emmanuel Caux and Sandrine Bottinelli (IRAP) and two M2 students– the analysis of close to 1,000 lines in more than 100 metastable levels (> 50 for Fe II alone). We have also detected an accretion flow toward HD42111, with broad wings and a slight asymmetry that we model as an inflow, with gas very close to the star wrapping around the stellar disk at much higher orbital velocities. This work is in progress. We also study the case of the double star HD256 (HR10) with a debris disk around each star (Montesinos et al, 2019). The disk lines are double, with variable ΔV. Our focus will be on studying their differences and similarities, in view of their origin and evolution in parallel.
Submitting proposals to observe more of these disk spectra while STIS is still operating is an important goal, in particular to make sure that these spectra will be available when planets are discovered within the respective circumstellar environments.

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