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YOUNG STARS IN TAURUS: A SEARCH FOR GAS TRACERS IN PROTOPLANETARY DISKS WITH SPITZER IRS SPECTRA.

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Abstract. In order to understand the structure and evolution of proto-planetary disks is fundamental to study the gas, which represents the ∼ 99% of their mass. But its properties are not yet well constrained because its detection is a difficult task. Dust, although a minor constituent of disks dominates the opacity, therefore it is much easy to observe. Our current knowledge of disks is largely based on the study of the emission from the dust. In the last few years, several detections of gas tracers in the mid-infrared have been reported, in particular [Ne II] (12.81 μm) whose origin is somehow controversial.

We have started a search for gas tracers in a sample of low-mass pre-main sequence stars in the Taurus Molecular Cloud. This study is based on archival observations of young stellar objects done by the *Spitzer Space Telescope* with the IRS high-resolution module spectrometer (R=600). Our sample contains 70 objects, we have detected emission lines from ionized gas and molecular rotational lines in 23 of them. We have fitted the line profiles and obtained line fluxes, with the aim to look for correlations with stellar parameters such as L_X or mass accretion rate in order to test the mechanism at the origin of the lines (irradiation, shocks, thermal, etc.). We present a review on our current understanding of gas in young stars and present the results from our study of the Taurus Molecular Cloud through *Spitzer* spectra.

1 Introduction

To understand the formation of planetary systems it is crucial to start by studying the processes leading to the formation of stars, such as the initial conditions of pre-stellar cores, the chemistry, composition and evolution of proto-planetary disks, etc. Although gas is the main component of disks (99%), the dust dominates the opacity becoming much easier to observe. Nevertheless, gas can be probed through rotational lines of CO and H_2 at near-IR, mid-IR and mm wavelengths. Theoretical studies suggest that irradiation of the circumstellar disks from high-energy photons can heat up the circumstellar material, heating and ionizing the gas and forming emission lines, mainly [Ne II] (12.8 μm), [Ne III] (15.6 μm), [Fe I] (24.0 μm) and [Fe II] (17.9 μm). Additional rotational molecular gas lines of H_2 (12.3, 17.0 μm) may also be detected. Although the origin of the lines is not yet clear, the absorption of stellar X-rays is an obvious candidate (Glassgold et al. 2007), but alternative models include the ionization by extreme UV photons, strong shocks, or cosmic rays.

In the last few years there has been an increasing number of studies reporting the detection of gas tracers in the mid-infrared. Pascucci et al. (2007) have observed six low-mass pre-main sequence stars with optically thick disks using the *Spitzer Space Telescope*. They have detected emission of [Ne II] in four of them. Lahuis et al. (2007) have also used *Spitzer* to obtain spectra for a sample of 76 low-mass pre-main sequence stars detecting emission from [Ne II] in ∼ 20% of the sample, and [Fe I] in ∼ 9% of them, but also [Fe II], [S III], and H_2 in a smaller number. Bitner et al. (2008) have detected H_2 emission in 6 out of 29 young stars observed in the

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near-infrared. Güdel et al. (2009) have detected [Ne II] in *Spitzer* spectra of 59 out 93 young stars. Flaccomio et al. (2009) have sampled the ρ Ophiuchi cluster in both X-rays (XMM-Newton) and mid-infrared (*Spitzer*), among the 28 observed young stars, [Ne II] emission has been detected in 10 sources, while [Ne III] has been detected in one case.

2 Sample

We have focused our study on the Taurus Molecular Cloud (TMC). This nearby star-forming region is indeed the ideal laboratory to study the low-mass star formation process; its distance (137 pc, Torres et al. 2007) allows us to observe fainter sources with no influence of high-mass young stars. The TMC has been observed in the X-rays with *XMM-Newton* (the XEST survey has covered ∼5 square degrees of the TMC, Güdel et al. 2007), and in the infrared with *Spitzer* (Spitzer Taurus Project covering ∼43 square degrees, Padgett et al. 2007).

This study is based on archived observations from the *Spitzer Space Telescope* using the Infrared Spectrograph (IRS) and its high resolution module (SH), with a resolving power of R∼ 600 for a wavelength coverage between ∼ 9 and ∼ 20 μm. Observations are mainly part of GTO programs (Guaranteed Time Observations).

Our sample accounts for 70 low and intermediate mass pre-main sequence stars; 8 Class I objects, 36 Class II, 4 Class III, 4 intermediate-mass Herbig stars. 7 objects are classified in the literature as both Class I and Class II. Furthermore, 11 objects have no classification in the literature.

3 Method

3.1 Data analysis

We have retrieved the data from the Spitzer Science Center. We have started our analysis from the post-BCD data, i.e.; spectra extracted automatically by the pipeline as they arrive from the spacecraft. The main problem encountered has been the lack of dedicated background observations for the main part of the sources in our sample, probably because it was thought that the background emission in Taurus was not contributing significantly. But the mid-infrared background comes predominantly from zodiacal light at IRS wavelengths and it can contribute significantly. Sky observations also help to alleviate the effects of rogue pixels (pixels with abnormally high dark current and/or photon responsivity).

In a first step we have used the interactive tool IRSCLEAN_MASK in order to create masks for the rogue pixels from the BCD images. Once the images are free from obvious rogue pixels we have re-extracted the spectra using SPICE (Spitzer IRS Custom Extraction).

In order to be sure that the lines detected were emitted from the source and they were not coming from the background or a nearby contaminating source, we have carefully examined the echellogram for each spectrum. In Fig.1 we present an example for the [Ne II] line. The echellogram displays in a 2D image the spectral order (10 for the SH module) and the wavelength. We have considered two regions with no emission lines adjacent to the position of the line studied. These two regions were used as local background plus stellar continuum; they were averaged and then subtracted to the region were the line is located. If after this procedure the line was still present, we considered that the emission was coming from the star.

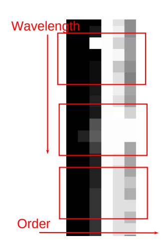

Fig. 1. Example of the echellogram image showing the [Ne II] line (12.8μm) in the 15$^{\text{th}}$ order. The middle box shows the position of the line, the upper and lower boxes show the regions used as local background plus stellar continuum. Wavelengths are represented in the vertical direction and the spectral order in the horizontal direction.

3.2 Line Fitting

Once we solved the problem of lack of background measurements using the procedure described in 3.1, we fitted the line profiles in order to obtain their luminosity. We have focused our search in the emission lines from H_2 (12.3, 17.0 μm), [Ne II] (12.8 μm), [Ne III] (15.6 μm), [Fe II] (17.9 μm), and [S III] (18.7 μm). The lines have been fitted with a function including a gaussian component plus a linear polynomial component to account for the adjacent continuum. All the parameters of the function were left free to vary. A detection is claimed when the peak of the line is three times higher than the continuum standard deviation in the wavelength range of interest (the range typically used was 0.6 μm). The FWHM obtained from our fits were consistent with the FWHM expected for the IRS spectral resolution.

4 Results

4.1 Detections

We have detected the [Ne II] line in 13 objects representing the 18% of the sample. This detection rate is consistent with the result from Lahuis et al. (2007) where [Ne II] has been detected in a 20% of the sample. The main difference between Lahuis et al. (2007) and this work is that our sample is based only in the TMC. In contrast Lahuis et al. (2007) have used a mixed sample with stars from different star-forming regions; Chamaeleon, Lupus, Serpens, Perseus, and Ophiuchius. Flaccomio et al. (2009) have detected [Ne II] in 10 sources out of a sample of 29 young stars in Ophiuchius.

Among the objects in our sample with [Ne II] detections there is one class I, seven class II, four sources with ambiguous classification class I/II and one Herbig star. The [Ne III] line was detected in 1 class II source with no detection of [Ne II]. H_2 (12.3 μm) is detected in 4 sources; one class II, two class III, and one with unknown classification. H_2 (17.0 μm) is detected in 5 sources; two class II, one class III, and two sources with unknown classification. Only in 2 sources there is the detection of H_2 at both wavelengths. [Fe II] is detected in 4 sources; two class II, one class I/II, and one class III. Finally, [S III] is not detected in any star of our sample. Figure 2 shows some of the lines detected in our sample; Tau-2 is a class I object; Tau-4, is a class II, Tau-6 and Tau-8 are class III, Tau-7 and Tau-9 are class I/II, Tau-5 has unknown classification.

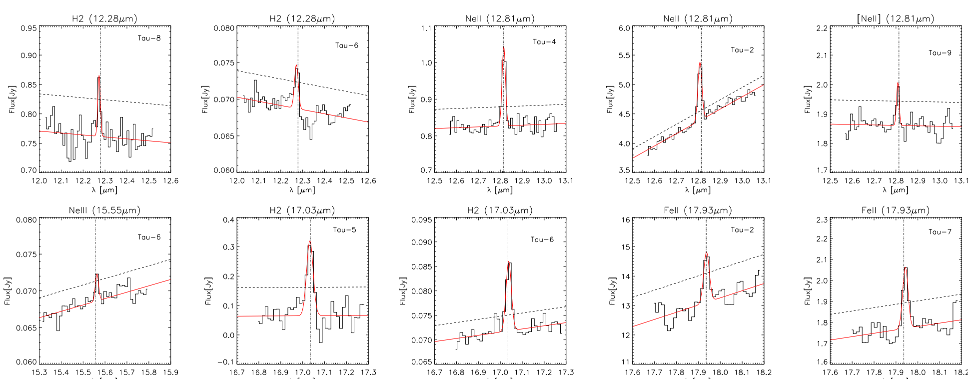

Fig. 2. Examples of detected lines from gas tracers in our sample of young stars in Taurus. The spectra are plotted as histogram in solid black line, the red solid line shows the fitted continuum plus line profile, and the black dashed line shows the 3-sigma continuum level.

4.2 Correlations

The high level of detection of the [Ne II] line has prompted us to search for possible correlations between the luminosity of the line, and different stellar parameters such as mass, mass accretion rate, X-ray luminosity (L_X), and Hα equivalent width (Figure 3). The equivalent width of the Hα line (seen usually in emission in young stars) is commonly used to differentiate between accreting and non-accreting stars; Hα(EW) $>$ 20 Å accreting stars, and Hα(EW) $<$ 20 Å non-accreting stars (Martin 1997).

For each parameter we have performed a Spearman's statistical test to probe the level of correlation. A significant correlation is found between the [Ne II] line luminosity and the mass accretion rate (significance of 0.10, where small values in the range [0,1] indicate a significant correlation), a weaker correlation is found with the equivalent width of the Hα line (significance of 0.35). No correlation is found with L_X and stellar mass (significance higher than 0.54).

Previous works have also explored the possibility of these correlations. The main drawback of early studies has been the reduced size of the samples. The first study of Pascucci et al. (2007) suggested a correlation with X-ray luminosity based on four detections. Espaillat et al. (2007) increased the sample to seven objects and did not find any evident correlation between $L_{[NeII]}$ and L_X, but they did find a correlation with mass accretion rate. Flaccomio et al. (2009) have found no correlation with L_X based on 10 detections. A correlation is found instead with disk mass accretion rate. In the sample of Güdel et al. (2009) based on 93 sources and 59 detections, there is a trend between $L_{[NeII]}$ and L_X and mass accretion rate, although with a large scatter. A correlation is found instead with jet/outflow parameters; $L_X \cdot L$[O I] at 6300 Å.

The lack of correlation between $L_{[NeII]}$ and L_X in our sample goes in the same direction than previous studies and would indicate that the ionization of Ne is not directly related to the X-ray irradiation from the central star, as predicted by the X-ray heating model of Glassgold et al. (2007). In our sample, the ionization of Ne appears to be related with accretion.

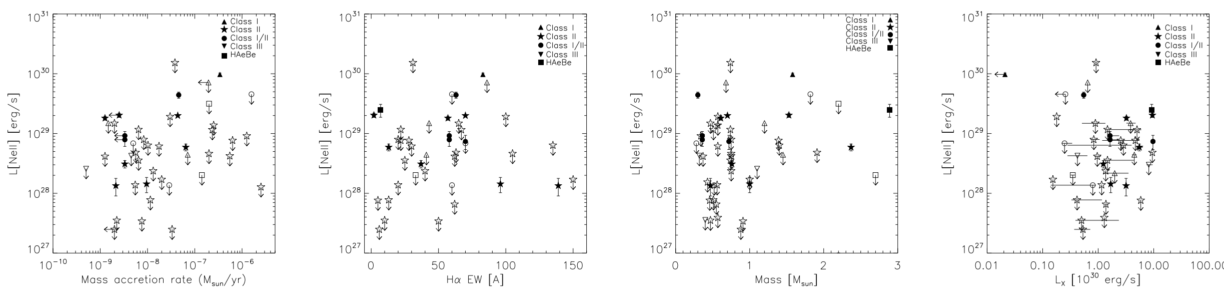

Fig. 3. Attempted correlations between the luminosity of the [Ne II] line and the stellar parameters; mass accretion rate, Hα equivalent width, stellar mass, and X-ray luminosity. These values were taken from the literature. Each symbol represent a different class of object: class I objects are represented by upwards triangle, class II objects by stars, class I/II objects by circles, class III by downward triangles, and herbig stars are represented by squares. The filled symbols indicate the [Ne II] detection, while empty symbols indicate upper limits.

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References

Bitner, M. A., Richter, M. J., Lacy, J. H., Herczeg, G. J., Greathouse, T. K. et al. 2008, ApJ, 688, 1326

Espaillat, C., Calvet, N., D'Alessio, P., Bergin, E., Hartmann, L., et al. 2007, ApJ. 664, L111

Flaccomio, E., Stelzer, B., Sciortino, S., Micela, G., Pilliteri, I., Test, L. 2009, 2009arXiv0906.4700F

Glassgold, A. E., Najita, J. R., Igea, J. 2007, ApJ, 656, 515

Güdel, M., Briggs, K. R., Arzner, K., Audard, M., Bouvier, J., et al. 2007, A&A, 468, 353

Güdel, M., Lahuis, F., Henning, T., et al. 2009 in prep. http://www.ipac.caltech.edu/spitzer2008/talks/ManuelGuedel.html

Herczeg, G. J., Najita, J. R., Hillenbrand, L. A., Pascucci, I. 2007, ApJ, 670, 509

Lahuis, F., van Dishoeck, E. F., Blake, G. A., Evans, N. J. II. 2007, ApJ, 665, 49

Martin, E. L., 1997, A&A, 321, 492

Padgett, D., McCabe, C., Rebull, L., Noriega-Crespo, A., Carey, S., et al. 2007, AAS, 211.2904P

Pascucci, I., Hollenbach, D., Najita, J., Muzerolle, J., Gorti, U., et al. 2007, ApJ, 663, 383

Torres, R. M., Loinard, L., Mioduszewski, A. J., Rodriguez, L. F., 2007, ApJ, 671, 1813