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OBSERVATIONS AT THZ FREQUENCIES WITH CONDOR

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Abstract. The CO N^+ Deuterium Observations Receiver, CONDOR, is one of the very few existing THz heterodyne receivers in the world. It covers a frequency range between 1.25 and 1.53 THz (240μm - 196μm). CONDOR was built with a focus on observing star forming regions, using high-J CO lines H_2D^+ and N^+ In November 2005 we tested CONDOR on the APEX telescope, and successfully observed CO 13-12 in several regions in Orion. In FIR4 we find a surprisingly narrow CO 13-12 line width (5.4 km/s), from which we conclude that the hot gas is probably radiatively heated rather than shock excited. The observations of NGC2024 reviled additional hot gas. In order to model the CO lines between J= 3-2 and J=13-12 consistently a model with molecular gas in 4 different layers is required. High spectral resolution observations in the THz regime allow us not only to probe gas otherwise difficult to observe, but also to obtain information about the structure and kinematics of the source.

1 Introduction

To this data there are very few astronomical (and in fact also laboratory) observations at THz frequencies (1-10 THz,300μm-30μm) at high spectral resolution. This is partly due to the poor (Earth) atmospheric transmission at these frequencies, partly due to the difficulties in building heterodyne receivers above 1 THz. However, this frequency regime harbors a multitude of astronomically interesting molecular and ionic transition lines. The excitation energy of these lines mostly lie between a few tens to a few hundred Kelvin, low enough to be excited in the warm to hot interstellar medium. Therefore high spectral resolution observations at THz frequencies provide an ideal tool to study the chemical and kinematic properties of the ISM, e.g. in star forming regions.

The CO N^+ Deuterium Observations Receiver (CONDOR) is one of only two heterodyne THz receivers currently in use. CONDOR was built with a focus on studying star formation processes. It covers a frequency range of 1.25 to 1.53 THz (240μm - 196μm) and can currently simultaneously observe 0.8 GHz (about 160 km/s). Its

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spectral resolution depends on the backend used, but lies usually around 100 kHz (0.02 km/s). The name of the instrument contains the molecules/ions we are most interested in observing: High-J CO transition lines (J 11-10, 12-11, 13-12) trace hot and dense molecular gas. The fine structure line of N^+ at 205μm is the third strongest emission line in the Milky Way as observed by COBE (Fixsen et al. 1999) and probably stems from the Warm Ionized Medium as well as from HII regions around young stars. The third focus lies on observations of the ground transition of p-H_2D^+. It is the key element in the formation of all deuterated molecules in cold environments, the last observable tracer for the kinematics when all other molecules are frozen onto dust grains and it is chemically very interesting. CONDOR is a modular receiver and can in principal be used on any appropriate telescope. We have focused on deploying to the Atacama Pathfinder EXperiment (APEX) and as a low frequency extension of German REceiver At THz-frequencies (GREAT) on the Stratospheric Observatory For Infrared Astronomy (SOFIA). Here we will describe our results from the first successful test observations of CONDOR on APEX.

2 CONDOR on APEX

CONDOR obtained its first light observations on the APEX telescope (Wiedner et al. 2006). APEX is located in the Atacama dessert, a very dry site at an altitude of 5100m. In spite of it being one of the best sites on the ground the transmission at THz frequencies only reaches about 30% in the atmospheric windows. With a primary dish of 12m the theoretical main beam size of CONDOR is 4.3". From the surface accuracy of the dish of 18 μm and a panel accuracy as good as $\sim$6 μm we expect, that there is a $\sim$ 72" error beam. The coupling efficiency to the main beam is about 0.09 (from Mars scan), the efficiency to the main plus error beam is about 0.4 (from measurements in the Moon). For pointing drift scans on Mars were used and we estimate an accuracy of better than 7" for our observations. We reached noise levels of 13K at 1km/s resolution in 10 minutes on-source integration time. During these first tests we observed 3 astronomically interesting objects: IRc2 (which is described in a contribution to this conference by Volgenau, and also in Volgenau et al. 2007) FIR4 (see below and Wiedner et al. 2006) and NGC2024 (see below and Emprechtinger et al. 2007).

3 Orion FIR4

CONDOR's first observations on a scientific target were made under excellent weather conditions (19% transmission along the line of sight) (see also Wiedner et al. 2006). The CO 13-12 line was detected from a hot core in OMC-1, alternatively known as FIR4 and S6, which lies either at or near the interface of the Orion A (M42) HII region and a region of compressed molecular gas (see Fig. 1). Broad line widths of numerous molecular lines (e.g. Batrla 1983) indicate that Orion FIR4 is a site of high mass star formation. Furthermore the shock stimulated SiO emission (Ziurys & Friberg 1987) shows that FIR4 is at the vertex of several outflows with $\pm$15km/s. To our surprise the line width of the CO 13-12 emission is, however, quite narrow and there are no apparent line wings, see Fig. 1. The best Gaussian fit to the line has a peak temperature of 210 K, a FWHM of 5.4$\pm$0.3km/s and a central velocity

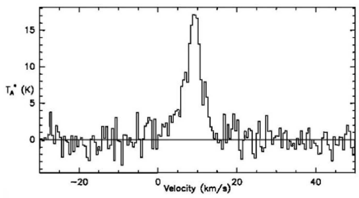

Fig. 1. CO J=13-12 transition of FIR4 in Orion. In order to get main beam brightness temperatures one needs to multiply T_A^* by 11.

of 9.0±0.1 km/s. Therefore it is unlikely that the CO J=13 state is excited by shocks. It is also unlikely that the emission stems from molecular formation in the post shock phase of a C-type shock, as the CO abundance hardly increases (Bergin et al. 1998). The main conclusion of this observation is hence that the hot gas in FIR4 is probably radiatively excited. We estimated the physical properties of the emitting region by using fluxes from multiple CO transitions as input to an escape probability code by Stutzki & Winnewisser (1985). The most likely fit corresponds to a density of $1.6\pm0.7\times10^5$cm^{-3}, a temperature of 380±70K and a total CO column density of $6.4\pm2.0\times10^{17}$cm^{-2}.

4 NGC2024

NGC2024 is a HII region in Orion embedded in a molecular cloud. As seen from Earth the observer first encounters a thin ridge of molecular gas, then the HII region, then a dense molecular cloud (e.g. Barnes et al. 1989). The HII region contains several young stars, of which IRS2b is mainly ionizing it. It expands into the dense molecular cloud and may trigger star formation. Graf et al.(1990 & 1993) have observed this region in mid-J CO lines (J=7-6) and have determined the physical properties of the for- and background molecular cloud. With CONDOR the observations could be extended to higher-J transitions and the previous model improved. CONDOR observed NGC2024 in a cut at 5 different location, however, we focused on the location of IRS3 in the analysis. In order to get a rough estimate of the physical conditions of the gas emitting high-J CO lines the integrated intensities of our CONDOR observations together with unresolved ISO observations of ^{12}CO lines from J_{up}=12 to 17 by Giannini et al. (2000) were used as input to the escape probability code. The model suggests a column density of $4.7\pm0.3\times10^{16}$, temperatures between 270 to 410K and H_2 densities between 3 to 9×10^5cm^{-3}.

However, the above model cannot take the complicated line shapes of the mid and low-J CO lines into account and can therefore only predict the physical conditions of the hot gas integrated over velocity. In order to describe the region more fully we also observed ^{12}CO 3-2, ^{13}CO 3-2, ^{12}CO 6-5 and ^{13}CO 6-5 and used these lines as input to a 1-dimensional radiative transfer code (SimLin, Ossenkopf et al. 2001). The results of the fit are shown in Fig. 2. In order to get these fits, the for- and the background component had both to be subdivided into two parts. The model consists of a 15-30K warm, 5×10^5cm^{-3} foreground component extending over 6×10^6cm, followed by another foreground layer that increases in temperature to 40 K and in density to 10^5

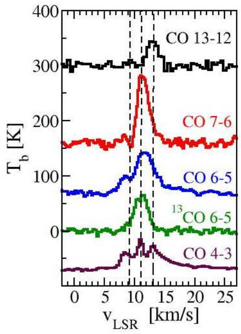

Fig. 2. ^{12}CO 13-12, ^{12}CO 7-5, ^{12}CO 6-5, ^{13}CO 6-5, ^{13}CO 4-3 observations of NGC2024.

over the following 10^{17}cm. Behind the HII region there is a hot interface region of 330 - 75 K with high densities of $9{\times}10^6$ cm, followed by a slightly cooler 75 K layer of the same density and extending over $8{\times}10^{16}$ cm. There might also be additional colder gas, which our observations are not sensitive to. This analysis shows that velocity resolved observations of tracers of different physical conditions are necessary to get a full picture of such complex star forming regions as NGC2024.

5 Summary and outlook

CONDOR has been successfully deployed to the APEX telescope and was able to obtain scientifically interesting first light observations. The observations show that velocity resolved spectra in the THz domain can significantly help us to understand the physical and chemical conditions of the gas. With the THz observations of the high-J CO transitions, e.g., we can explore the hot gas in the vicinity of newly forming stars and speculate about the physical processes taking place there. Once a modified CONDOR is installed on SOFIA we will extend our investigations to the coldest molecular regions using H_2D^+ and the ionized gas by observing N^+.

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