ZEUS on the CSO: Probing Star Forming Regions over the History of the Universe

From the time when the first stars and galaxies formed to the present time the process of star formation underwent tremendous changes. Although the basic mechanism of star formation stayed the same, namely the gravitational collapse of a gas cloud till it reaches the temperature to ignite nuclear fusion, the rate at which stars are formed differs greatly over the history of the Universe. This is because star formation is closely linked with the evolution of galaxies and their environment, which ultimately affects the physical conditions of the star forming gas clouds. The amount of gas mass that gets converted into stars per year serves as a measure for the star formation rate. The Milky Way, for example, converts just a few (2 to 3) solar masses of gas into stars per year. However, to compare the star formation rate at various epochs in the history of the Universe it is necessary to take the expansion of the Universe into account and the star formation rate is therefore measured within a co-moving volume; that is a volume that expands with the Universe. Surveys probing the star formation rate over the history of the Universe that were done in the ultraviolet (UV), optical, and near-infrared (near-IR), as well as in the far-IR and submillimeter wavelength regimes indicate a rise in the star formation rate per co-moving volume from the time when the Universe was about 1 billion years old ($z \approx 6$), when the first stars and galaxies have again re-ionized the gas in the Universe, till the Universe reached an age between 2 and 3.5 billion years ($z \approx 2-3$). After this peak the star formation rate per co-moving volume started to fall again and still declines at our present time. But nevertheless, even in our local Universe a small fraction of galaxies, the Ultraluminous Infrared Galaxies (ULIRGs), also have enormous luminosities (power), which are mainly caused by an enormous burst of star formation (a starburst), and partly by nuclear activity due to accreting gas onto a massive Black Hole. Usually, the higher the luminosity, the more important the active nucleus becomes. Almost all of the luminosity from these galaxies emerges in the infrared wavelength regime. In addition, these galaxies are so dusty that it is often impossible to even see the star forming regions in the center of these galaxies in the optical and near-IR bands. Thus, observations at long wavelength are most suitable to study the gas in these star forming regions and uncover the causes for the enhanced star formation activity.

Our group at Cornell University, led by Prof. Gordon Stacey, has built a grating spectrometer, ZEUS (Fig. 1), that operates in the submillimeter wavelength regime and that is specifically designed to study the star formation activity in the early Universe and in ULIRGs. The acronym ZEUS stands for Redshift (Z) Early Universe Spectrometer. The grating receives light of all wavelengths and spreads the wavelengths out into a "rainbow" in the image plane of our detector. By placing a detector array along the direction of this "rainbow" each pixel detects a different wavelength and therefore the row of pixels makes the spectrum. ZEUS currently uses a 1×32 thermistor sensed bolometer array that was provided by Harvey Moseley's group at Goddard Space Flight Center as its detector. When a photon gets absorbed by a bolometer its energy is converted into heat and we measure an increase in temperature as our signal. To optimize the performance of the detector it is cooled to a temperature of about 0.25 degrees above absolute zero, so that a little bit of increase in heat results in a relatively large change in detector temperature. Since bolometers are sensitive to all wavelength ZEUS also employs a series of additional filters. The final bandpass filters are directly mounted at the entrance slit of the detector enclosure. They consist of a 350 μm and 450 μm bandpass filter budded adjacent to each other, thereby spectrally splitting the detector in half. Thus ZEUS takes 16 pixel spectra in each of the 350 and 450 μm telluric windows of the same spatial position on the sky simultaneously. The resolving power is about 1000, so that spectral lines

Figure 1: Former graduate student Steve Hailey-Dunsheath and Prof. Gordon Stacey preparing ZEUS for observation on the right Nasmyth platform of the CSO.

separated by 1 part in 300 are independently measured. The instantaneous bandwidth of a single integration is about 5000 km/s in each of both bands. Given this broad bandwidth ZEUS can detect several lines simultaneously, especially the CO(7-6) and [CI] line, which are only separated by 1000 km/s. By tilting the grating ZEUS can cover the entire wavelength range of the telluric windows. ZEUS shows excellent performance with an equivalent single side band receiver temperature of about 55 K or less at both the 350 μm and 450 μm telluric windows. ZEUS was the PhD thesis project of Steve Hailey-Dunsheath and who just defended his thesis in December 2008.

With our grating spectrometer ZEUS, we probe the physical properties of the star forming regions using mid-J rotational transitions of ^{12}CO (J=6$\rightarrow$5, 7$\rightarrow$6, and 8$\rightarrow$7), of isotopic ^{13}CO (J=6$\rightarrow$5, and 8$\rightarrow$7), as well as the [CI] 370 μm fine structure line and far-IR fine structure lines (especially the [CII] 158 μm line) that are redshifted into the submillimeter telluric windows. Carbon monoxide (CO) is the second most abundant molecule in interstellar space after molecular hydrogen and carbon is the fourth most abundant element in the Universe (after H, He, and O). The far-IR (50 to 300 μm) fine structure lines are important coolants for all phases of the interstellar medium and excellent probes of the physical state of the gas as well as the numbers, and types of stars. However, the far-IR not accessible from ground-based observatories. But due to the expansion of the Universe these lines will be redshifted into the submillimeter wavelength regime, which is accessible from observatories on high and dry sites, like the CSO on Mauna Kea, so that it is possible to observe these very important lines from galaxies in the early Universe. By comparing the observed lines with theoretical models of line emission from neutral gas clouds exposed to ionizing starlight or the very intense and high energy photons from active galactic nuclei, we deduce temperature, density, and mass of the gas. From the gas properties we can then infer the excitation mechanism of the gas. If the energy comes from photons, does it come from stars (which type?), or AGN? Is the gas excited by cosmic rays from supernova, or perhaps by collisions between interstellar gas clouds?

Fig. 2 shows a sample of CO(6-5), CO(7-6) and [CI] spectra obtained with ZEUS. So far we have detected one or more of the mid-J ^{12}CO and ^{13}CO and [CI] lines from 20 galaxies (ULIRGs and lower luminosity galaxies). Our observations find large amounts of warm and dense molecular gas in ULIRGs with temperatures greater than 100 K and densities in the range of 10^4 cm^{-3} to 10^5 cm^{-3}. Although some warm and dense molecular gas is expected in star forming regions the

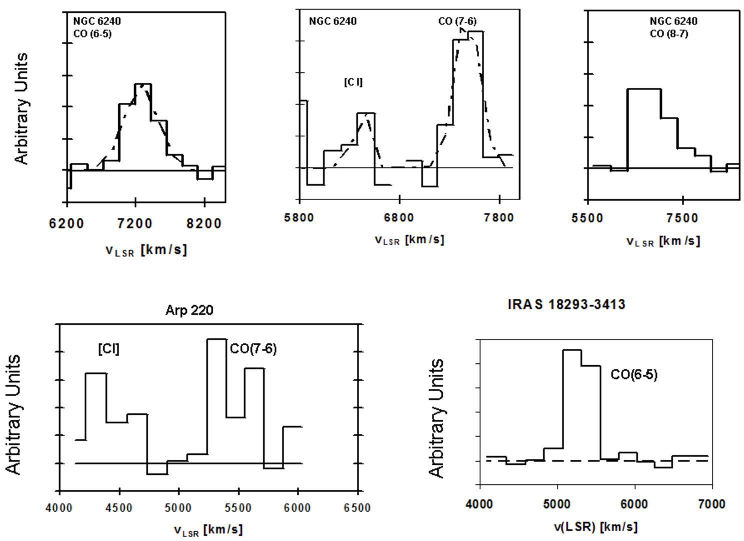

Figure 2: This sample of spectra taken with ZEUS on the CSO shows the ^{12}CO J=6→5, ^{12}CO J=7→6 and [CI] 370 μm, and ^{12}CO J=8→7 line from NGC 6240 as well as the ^{12}CO J=7→6 and [CI] 370 μm line from Arp220 and the ^{12}CO J=6→5 line from IRAS 18293-3413. All spectra of NGC 6240 have the same scale. The scale of the spectrum of Arp220 is twice the scale of the NGC 6240 spectra and the scale of the IRAS 18293-3413 spectrum is a factor of 10 weaker than the NGC 6240 spectra.

amount of warm molecular gas usually equals the amount of atomic gas. The finding of large masses of warm molecular gas poses a problem to the heating mechanism of the gas, which is usually due to photo-electric heating. In this process a UV photon ejects an energetic electron from a dust grain. This photo-electron then gives up its extra energy to the gas (heating it) through collisions with hydrogen atoms and molecules. However, UV radiation does not reach deep into molecular gas. Thus another heating mechanism is required to heat the bulk of the molecular gas. In a previous observation of the nearby starburst galaxy NGC 253, we also detected vast amounts of warm and dense molecular gas. The mass of the warm and dense molecular gas in this galaxy is more than 10 times the amount of the atomic gas. In this study we concluded that cosmic rays from supernovae are dominating the heating deep inside the molecular clouds and we made predictions for the strength of the isotopic ^{13}CO(6-5) line, which can be traced deeper into the molecular gas. With ZEUS on the CSO we have now detected the ^{13}CO(6-5) line from NGC 253 (Fig. 3) (Hailey-Dunsheath et al 2008). This is the first detection of ^{13}CO(6-5) from an extragalactic source. The observed intensity is as high as expected from our previous model and confirms our suggestion that vast amounts of cosmic rays from supernovae is the main heating source of the warm molecular gas in this galaxy. In addition to cosmic rays decay of supersonic turbulence through shocks within molecular clouds can also contribute to the heating. The extra heating sources that warm up the bulk of molecular clouds also suggests that the starburst will be terminated, since the elevated temperature in the molecular cloud increases the internal pressure and thus provides additional support against cloud collapse.

Up to now we have detected redshifted [CII] from 3 galaxies in the redshift range between $z = 1$ and 2 (Fig. 4) and another possible detection of [CII] from a galaxy at a redshift of just above 1. The redshift z indicates the factor by which the line is shifted to longer wavelength. A redshift of $z = 1$ corresponds to the wavelength being shifted by $1 + z = 2$. Thus, for a galaxy at redshift 1 the far-IR [CII] line at 158 μm will appear at a wavelength of 316 μm. By comparing our [CII] observations with far-IR continuum observations and using model calculations for photodissoziation

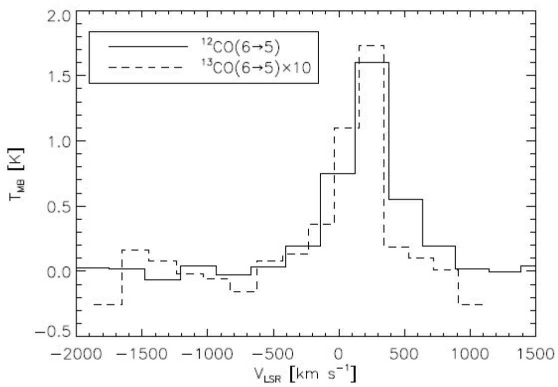

Figure 3: ^{12}CO J=6→5 and ^{13}CO J=6→5 from NGC 253, observed with ZEUS on the CSO

regions we derive the far-UV intensities in these galaxies. Since the far-IR continuum emission is reprocessed UV radiation from stars the derived far-UV intensity is proportional to the observed far-IR continuum, with the proportionality factor being the beam filling factor. Then by using this beam filling factor and the known beam size of our observations we can estimate a size for the star forming region. Our observations indicate that the star forming regions in our observed redshifted galaxies have sizes of several kiloparsec. For comparison, the distance between the sun the center of the Milky Way is 8.5 kiloparsec or 28,000 lightyear. This suggest that during the epoch when the star formation rate peaked in the evolution of the Universe galaxies with enhanced star formation exhibit galaxy-wide starburst. This is in strong contrast to the sizes of the starbursts in the ultra-luminous galaxies in the local Universe. In the current epoch starbursts occur in very compact localized regions in galaxies with sizes less than a few 100 parsec. The trigger mechanism that causes the starbursts in the local Universe and the much more massive starbursts in the early Universe, is most likely collisions between galaxies. However, as our observations indicate, this trigger mechanism affects the galaxies very differently, leading to extended starburst in the early Universe and compact starburst in the local Universe.

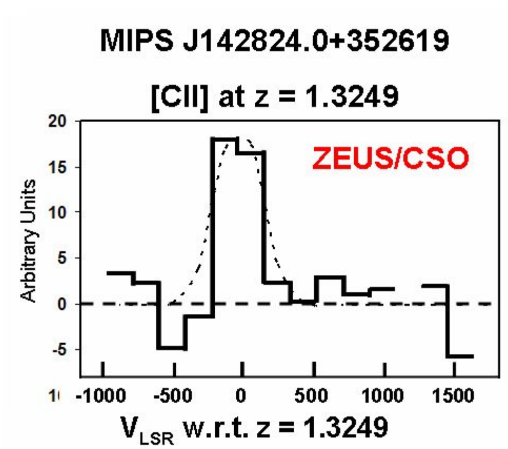

Figure 4: Redshifted [CII] 158 μm observed with ZEUS