Z-Spec: A MM-Wave Spectrometer For Measuring Redshifts Of Submillimeter Galaxies

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Abstract. We are building a background-limited, broadband millimeter-wave spectrometer (Z-Spec) for observations of CO rotational transitions from high-redshift dusty galaxies. The large instantaneous bandwidth (195 to 310 GHz) will enable redshifts of dust obscured galaxies to be unambiguously measured. Z-Spec uses a waveguide-coupled grating architecture in which the light propagation is confined within a parallel-plate waveguide. The grating is extremely compact compared to a classical free-space system. An array of silicon nitride bolometers cooled to 100 mK will provide background-limited performance. Z-Spec serves as a technology demonstration for a future space-borne far-infrared grating spectrometer.

Z-SPEC: REVEALING THE HISTORY OF THE DUSTY UNIVERSE

The far-infrared (FIR) part of the electromagnetic spectrum represents a key to understanding galaxy formation and active galactic nuclei. The cosmic FIR background radiation discovered by COBE [1,2,3] likely arises from intense starbursts and active galactic nuclei resulting from gravitational collapse that was triggered by galaxy interactions and mergers. Deep surveys with ISO, SCUBA and MAMBO resolved between 10% and 40% of the cosmic FIR background into individual sources [4,5,6]. These observations point to a new, rapidly evolving, population of high redshift (z>1), very luminous infrared galaxies.

However, important questions about infrared galaxies remain. What is the redshift distribution of this new population of infrared galaxies (i.e., what is the universal history of embedded star formation and nuclear activity)? Determination of redshifts is difficult since some galaxies are so dusty that they do not have observable optical counterparts, while others have multiple possible counterparts within the large submillimeter beams. The FIR fine-structure lines (e.g. [CII], [OI], [OIII]) are bright and could be used to measure the redshifts of these galaxies, but the narrow submillimeter windows do not permit routine observations of these lines from the ground. At 1 mm, the atmosphere becomes reliably transparent over a broad band

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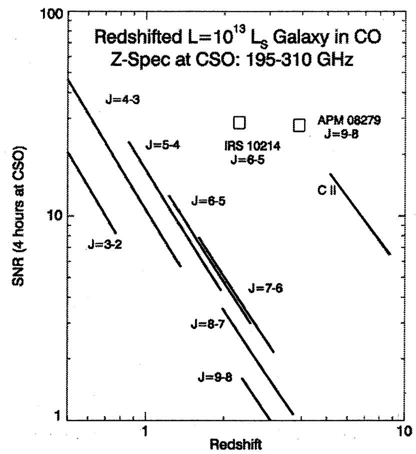

FIGURE 1. The feasibility of detecting high-redshift sources with a background-limited 1 mm spectrometer at the Caltech Submillimeter Observatory. Curves indicate the range of redshifts for which each CO line is observed in the 1mm atmospheric window. The CO line luminosities are taken as fractions of the total FIR source luminosity (Blain et al. 2000 [7]). The fractions vary from $3x10^{-8}$ to $3x10^{-5}$. The [CII] luminosity fraction is taken as $1x10^{-3}$. Sensitivity at the IRAM 30 m telescope will be 4-5x better.

(195-310 GHz), and for $0.9 < z < 4$, two or more CO transitions are always observable in this window. This provides an unambiguous redshift probe. For more nearby systems, ($z < 0.9$), the observations will constrain the redshift to be one of two discrete values easily distinguished with 100 GHz follow-up observations. Figure 1 demonstrates the feasibility of detecting high-redshift sources with a background-limited 1 mm spectrometer.

WAVEGUIDE-COUPLED DIFFRACTION GRATING: A NEW SPECTROMETER ARCHITECTURE

The Z-Spec concept combines a classical diffraction grating with a two-dimensional waveguide in a hybrid configuration (Figure 2). A radiating feedhorn (left) illuminates the faceted grating surface (bottom) with the radiation from the telescope. The radiation expands horizontally, but is confined to 2.5 mm vertically by conducting parallel plates. The top plate is shown partially cut away. The radiation is reflected and dispersed by the grating facets (still confined by the parallel plates) and refocused. Three reflected beams, corresponding to three different frequencies, are shown converging onto the focal surface (the arc starting from the left of the diagram and curving up the top) at three different locations. Receiving feed horns at the focal surface couple the radiation onto an array of bolometers.

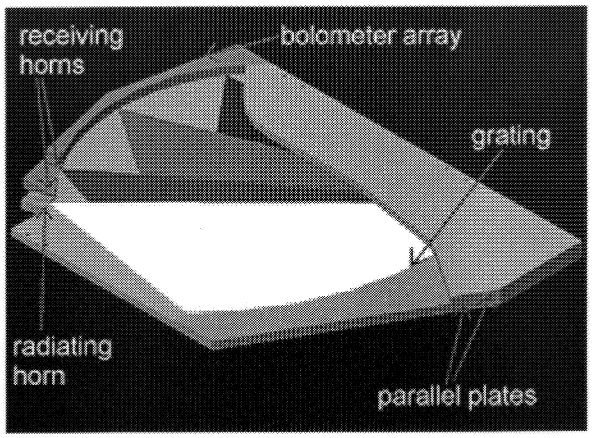

FIGURE 2. Schematic of a waveguide-coupled grating spectrometer.

We have built a millimeter-wave room-temperature spectrometer as a prototype. Since the number of bolometers and the size of the grating increase linearly with the spectral resolution, we chose a moderate resolution corresponding to 155 detector elements. The theoretical spectral resolution ranges from R = 350 at 310 GHz to R = 200 at 195 GHz. A resolution of R~800 would match extragalactic line widths. This design compromises resolution, total bandwidth, and size. With this prototype we have demonstrated the functionality of the waveguide grating (Figure 3).

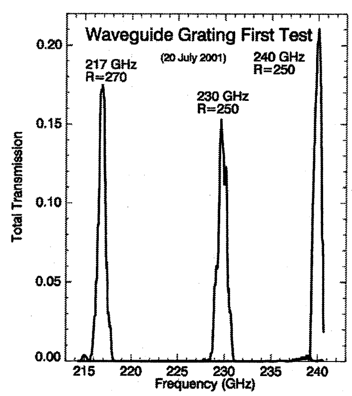

FIGURE 3. Results of the first warm testing of the grating spectrometer. We used a tunable power source for frequencies up to 240 GHz. The signal was coupled into and out of the spectrometer through custom feedhorns. The prototype feed horns were not yet gold plated and held to only modest tolerances. Consequently, they were the dominant source of loss in the system. From better fabrication of the horns and reduced waveguide losses upon cooling we expect a throughput as high as 70%. The intrinsic spectral resolution of the system is higher than shown because the plotted profiles include the convolution with a non-optimum receiving feedhorn. A measurement with an optimized feedhorn at 230 GHz yielded a resolving power of 320, very close to the theoretical value.

CRYOGENIC SYSTEM AND BOLOMETER ARRAY

The resolution of the spectrometer requires the bolometers to have noise equivalent powers (NEPs) of approximately 6×10^{-18} W $Hz^{-1/2}$ to achieve background-limited performance. An array of silicon nitride bolometers at an operating temperature of 100 mK can achieve this NEP. An adiabatic demagnetization refrigerator coupled to a closed-cycle $^4He/^3He$ sorption refrigerator (for pre-cooling the bolometers and grating and intercepting the heat load from the ^4He bath and bolometer bias/readout wires) will be used in Z-Spec.

FUTURE SPACE-BORNE APPLICATIONS

The millimeter-wave spectrometer will serve as a demonstration of the waveguide-coupled diffraction grating technology with efficient coupling to background-limited detectors. The waveguide coupled grating uses no moving parts, is completely light tight and its volume is two orders of magnitude smaller than a comparable classical system. These properties make it an excellent candidate for a spectrometer on-board a cold (4-5 K) infrared telescope in space, such as SPICA (formerly HII/L2), a proposed Japanese telescope with a 3.5 meter primary mirror [8]. An FIR spectrometer onboard SPICA would have spectroscopic sensitivity three orders of magnitude beyond planned far-infrared missions. Such capability would, for example, allow spectroscopic identification of all the galaxies in the 250 μm confusion-limited surveys of the Herschel Space Observatory.

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