# THE CASE FOR SPACE-BORNE FAR-INFRARED LINE SURVEYS

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## ABSTRACT

The combination of sensitive direct detectors and a cooled aperture promises orders of magnitude improvement in the sensitivity and survey time for far-infrared and sub-millimeter spectroscopy compared to existing or planned capabilities. Continuing advances in direct detector technology enable spectroscopy that approaches the background limit available only from space at these wavelengths. Because the spectral confusion limit is significantly lower than the more familiar spatial confusion limit encountered in imaging applications, spectroscopy can be carried out to comparable depth with a significantly smaller aperture. We are developing a novel waveguide-coupled grating spectrometer that disperses radiation into a wide instantaneous bandwidth with moderate resolution (R ~ 1000) in a compact 2-dimensional format.

A line survey instrument coupled to a modest cooled single aperture provides an attractive scientific application for spectroscopy with direct detectors. Using a suite of waveguide spectrometers, we can obtain complete coverage over the entire far-infrared and sub-millimeter. This concept requires no moving parts to modulate the optical signal. Such an instrument would be able to conduct a far-infrared line survey $10^6$ times faster than planned capabilities, assuming existing detector technology. However, if historical improvements in bolometer sensitivity continue, so that photon-limited sensitivity is obtained, the integration time can be further reduced by 2 to 4 orders of magnitude, depending on wavelength. The line flux sensitivity would be comparable to ALMA, but at shorter wavelengths and with the continuous coverage needed to extract line fluxes for sources at unknown redshifts. For example, this capability would break the current spectroscopic bottleneck in the study of far-infrared galaxies, the recently discovered, rapidly evolving objects abundant at cosmological distances. The role for line survey instrumentation will become acute as the detection rate of far-infrared galaxies dramatically increases with the next generation of space-borne and ground-based

bolometer cameras. A space-borne spectrometer can rapidly follow up Herschel/SIRTF far-infrared galaxies at wavelengths inaccessible from the ground, conduct deep line surveys, and even search for redshifted $H_2$ line emission from the first luminous objects.

## INTRODUCTION

Direct detectors, unlike hetrodyne systems, are not limited by fundamental quantum noise and can achieve background-limited sensitivity even under the very low backgrounds encountered in spectroscopy. Background-limited direct detectors combined with a cooled aperture promise a significant improvement in our capability to detect far-infrared spectral lines from galaxies as cosmological distances. Far-infrared lines can provide the redshifts and reveal the energetics of distant far-infrared galaxies. Furthermore, line emission from molecular hydrogen may be detectable at high redshifts in primordial galaxies undergoing the first episode of star formation. Because these distant objects may be at undetermined redshifts, we propose that moderate resolution spectroscopy with direct detectors over a large instantaneous bandwidth is attractive for future space-borne instrumentation. We shall show that the line survey speed possible in space is significantly higher than currently planned capabilities.

Unlike photometry, which encounters a confusion limit that varies as a function of angular resolution on the sky, spectroscopy offers the ability to distinguish multiple objects in a single beam by virtue of spectral discrimination. Thus the spectral confusion limit, set by the density of spectral lines, is much lower than the more familiar photometric confusion limit. If sufficient sensitivity can be achieved, spectroscopic line surveys may even be deeper than a photometric survey for a given aperture diameter. Several authors have even promoted deep spectral line surveys in blank regions of sky (e.g. Blain *et al.* 2000), but current sensitivities are far too low to make such surveys practical.

## ACHIEVABLE SENSITIVITY

Surveys for spectral lines are best carried out with a dispersive spectrometer, such as a grating. We are developing a compact 2-D waveguide spectrometer (WaFIRS) which operates in one polarization over a wide bandwidth (see C.M. Bradford *et al.* in these proceedings). We calculate the sensitivity achievable with a spectrometer with direct detectors as follows. We combine both detector and photon noise equivalent powers in quadrature,

$$NEP_{tot}^2 = NEP_{bol}^2 + 2hnQ.$$

The optical power absorber by the detector is

$$Q = \lambda I_\lambda R^{-1} \lambda^2 \eta_{opt} (N_{pol}/2),$$

where $\lambda I_\lambda$ is the specific intensity of the sky, including emission from the cosmic microwave background, interstellar dust, zodiacal dust, and thermal emission from the telescope. The total optical efficiency is $\eta_{opt}$, the number of polarizations detected is $N_{pol}$, the spectral resolution is $R = \lambda/\Delta\lambda$ and we assume single-mode throughput $\lambda^2$. For

WaFIRS we assume R = 1000, $\eta_{opt}$ = 0.5 and $N_{pol}$ = 1. The staring sensitivity to integrated line intensity in one Hz of audio bandwidth is thus

$$NEF = (A\ \eta_{opt}\ (N_{pol}/2))^{-1}\ NEP_{tot} \quad [W\ m^2\ Hz^{-1/2}],$$

where we have neglected the small factor of the choice of detector sampling of the spectrometer focal plane. The time to survey the available spectral bandwidth of an instrument to a given line sensitivity $\delta F$ is thus

$$T = 0.5\ (NEF/\delta F)^2\ (\Delta\nu_{instr}/\Delta\nu_i),$$

where $\Delta\nu_{instr}$ is the available spectral bandwidth of the instrument, and $\Delta\nu_i$ is the instantaneous spectral bandwidth available at a given moment during the observation.

We compare the achievable sensitivity with a grating spectrometer on a cooled telescope with planned instruments, SIRTF/IRS (http://sirtf.caltech.edu/SSC/IRS), Herschel (http://astro.estec.esa.nl/herschel/key_pubs.html), and ALMA (http://www.alma.nrao.edu/info/sensitivities) in Fig. 1. For ALMA, we assume broad 300 km $s^{-1}$ linewidths appropriate for galaxies, and 4 GHz of instantaneous bandwidth. With a 12 GHz instantaneous bandwidth, the ALMA survey times in Fig. 1 will be reduced by a factor of 3.

The purpose of this comparison is to motivate the need for wideband space-borne spectroscopy. We hasten to emphasize that the WaFIRS sensitivity only represents what is achievable, which is optimistic by definition, whereas the other instruments are designed with full noise budgets, and are generally in a high state of engineering development. In the case of IRS in particular, the full instrument has been assembled and tested and awaits launch. Furthermore WaFIRS requires large numbers of high sensitivity detectors, in quantities and background-limited sensitivities that exceed the current state of the art. The scientific role of a space-borne spectrometer with moderate spatial and spectral resolution, but with complete spectral coverage, is very complementary to ALMA with high spectral and spatial resolution, but with spectral coverage limited to atmospheric windows.

Nevertheless, the improvement in line survey speed in Fig. 1 is very large, more than 6 orders of magnitude for detectors with NEP = 1e-18 W/√Hz, and up to 9 orders of magnitude in the case of background-limited detectors. An additional 2 orders of magnitude of improvement would be obtained with a 10 m aperture such as the proposed SAFIR mission.

## SCIENTIFIC APPLICATIONS

Our proposed technology enables moderate resolution ($R = \lambda/\Delta\lambda \sim 1000$) spectroscopy of galaxies to determine redshifts and energetics. A distribution of redshifts determines the history of deeply embedded star formation and the earliest epoch of galaxy formation. Furthermore, with complete spectra, important questions about the nature of the galaxies can be resolved, such as the cooling rates, excitation conditions, and AGN fractions.

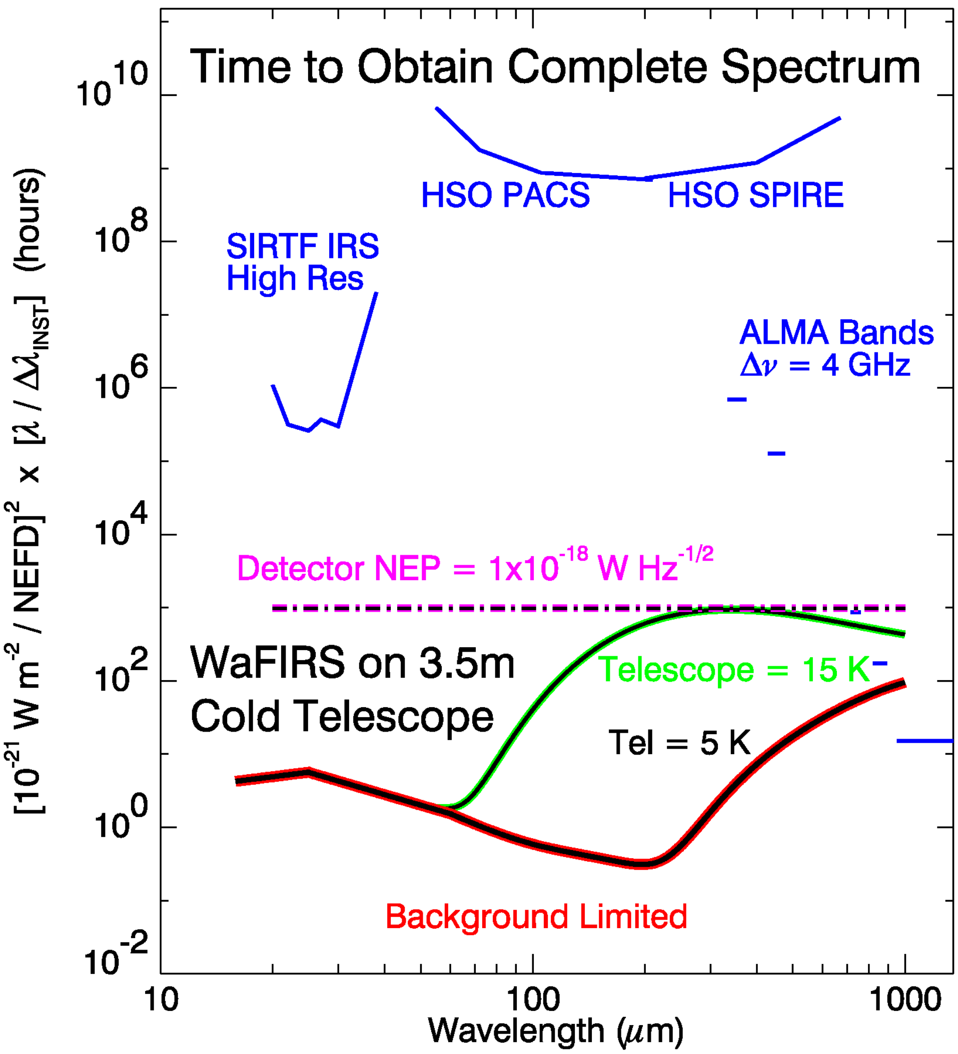


***Figure 1:*** *Spectral spectral line survey speed plotted for several instruments. The figure of merit, [1e-21 W m$^{-2}$/NEFD(5σ)]$^2$ [λ/Δλ$_{inst}$], gives the time required to survey for a line in an octave of bandwidth, to a 5σ sensitivity of 1e-21 W/m$^2$. This is the appropriate figure of merit for detecting lines at unknown redshift. We estimate the observation time required from a cooled 3.5 m space-borne telescope (WaFIRS) with existing NEP = 1e-18 W/√Hz detectors (dashed line) and background-limited detectors (green and red curves) for different telescope temperatures. This projected observing time is compared with the times required for SIRTF/IRS, Herschel, and ALMA.*

### *Follow-up of SIRTF and Herschel Far-Infrared Galaxies*

The redshift and far-infrared line strengths of virtually every Herschel/SIRTF galaxy should be detectable spectroscopically with WaFIRS on a 3.5 m telescope, as shown in Fig. 2. We estimate the minimum galaxy flux from the confusion limit of Herschel (Blain, Ivison, & Smail, 1998) and SIRTF/MIPS (Rieke *et al*, 1996). The lines in the figure are the expected [CII] 158 μm fluxes as a function of redshift for sources with fluxes corresponding the 5σ confusion noise level for each instrument. The FIR spectral energy distributions are assumed to be thermal dust emission greybodies ($T_{dust}$ =

40 K, $\beta$ =1.6, $\lambda_0$ = 25 $\mu$m). The line luminosities were derived by multiplying the bolometric FIR luminosities by $L_{[CII]}/L_{FIR}$ = 1 x $10^{-3}$ (e.g., Fisher 2000), where the observed FIR flux is equal to the 5σ confusion noise level. The bold line is the WaFIRS sensitivity assuming background-limited detectors. The predicted line flux initially drops with increasing redshift because the peak of the galaxy spectral energy distributions is being redshifted into the FIR bands. Therefore, fainter galaxies will be detected at the photometric confusion levels. The curves turn up steeply again beyond a redshift of a few because the luminosity of the observed galaxies at the confusion noise level is larger.

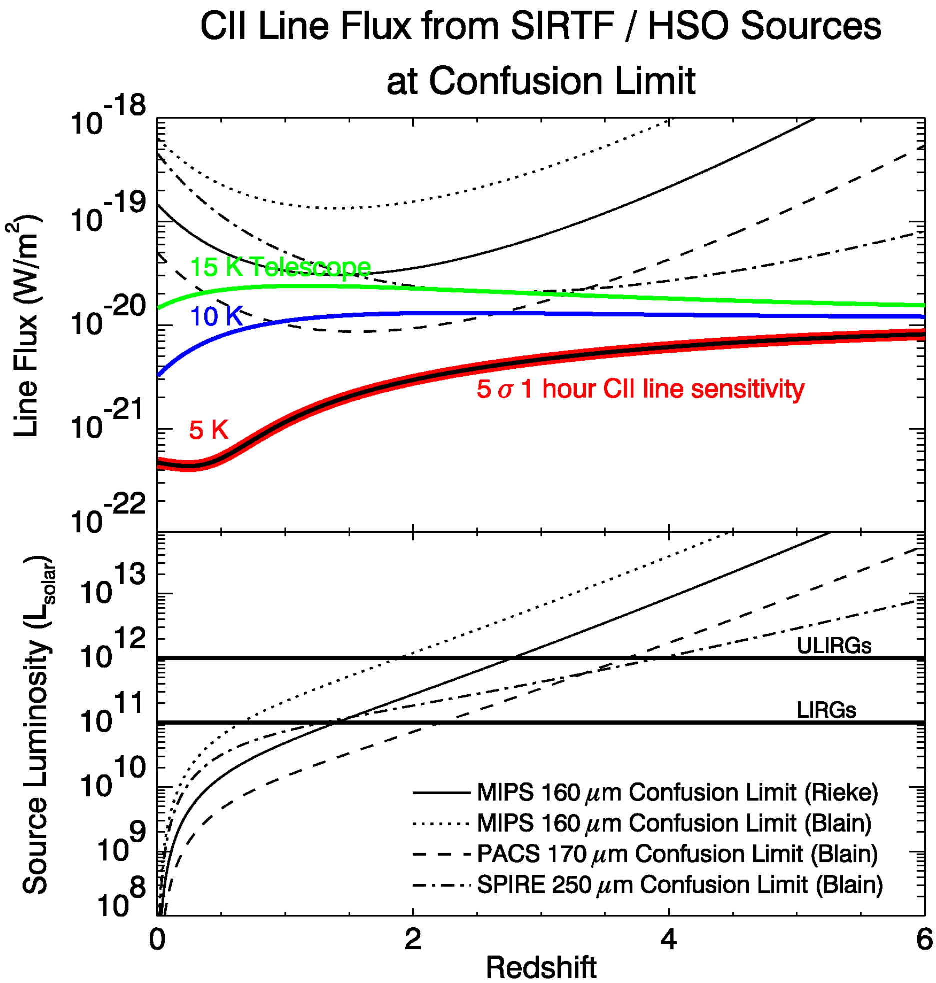


***Figure 2:*** *[CII] line emission from any object detected photometrically by SIRTF or Herschel is readily detected by the space-borne spectrometer. We assume a line-to-continuum ratio L(line)/L(bol) = 1 x* $10^{-3}$.

This analysis shows that for redshifts where the [CII] line is observable (z < 5), WaFIRS will be able to detect the [CII] line for all galaxies at the confusion noise levels of SIRTF and Herschel. For galaxies with fluxes at the 5σ confusion noise level, it will take a few minutes to detect the [CII] line with a signal-to-noise ratio of five at z = 2, and less time at the other redshifts. Galaxies at large distances, z > 5, must either be extremely luminous or lensed to be detected by HSO or SIRTF. They should be detectable in 1 hour of integration in faint atomic lines (e.g. NII, NIII, OI, OIII), with $L_{line}/L_{FIR} > 10^{-6}$. The redshift and far-infrared line strengths of virtually every Herschel or

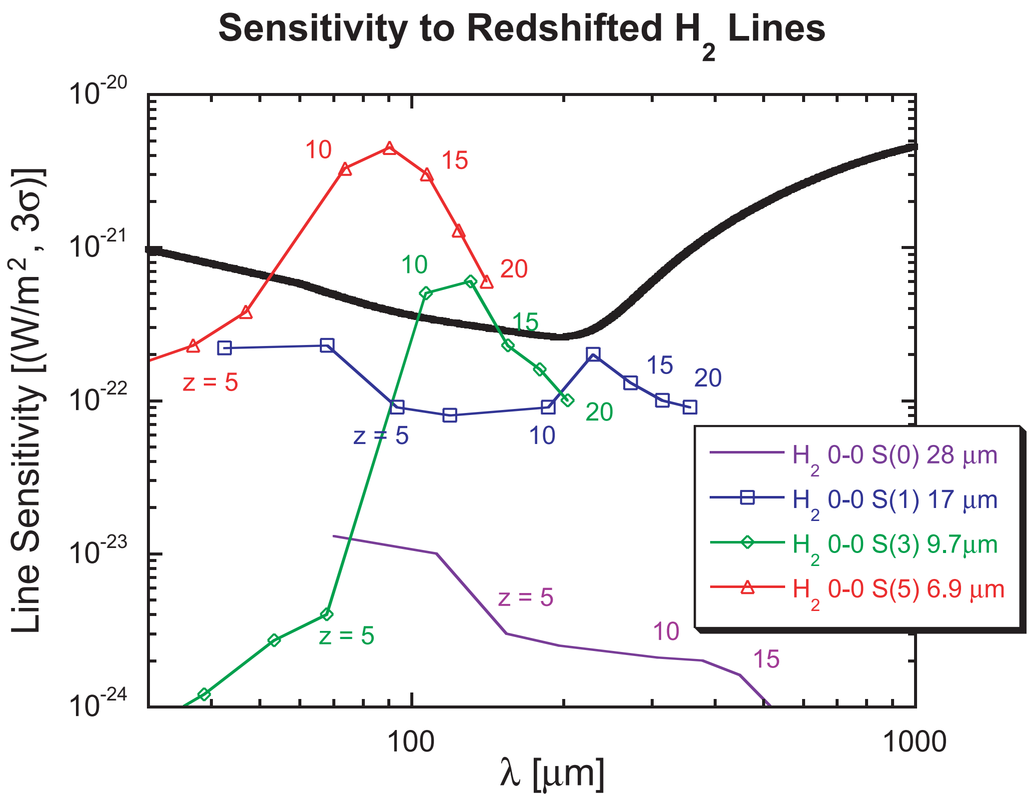


***Figure 3:*** *Molecular hydrogen line emission driven by the first generation of star formation, calculated according to the model of Ciardi and Ferrara (2000). Line emission is detectable out to large redshift (z = 20) in moderate integration time.*

SIRTF galaxy should be measurable. The high line survey speed makes it possible to survey a large fraction of the ~$10^5$ galaxies expected from a key-program survey with Herschel.

*Blind Spectral Line Surveys*

The high sensitivity of WaFIRS allows for such a deep spectral line survey for the first time. Although the spectral confusion limit is highly uncertain, we estimate that ~$10^2$ hours are required to reach line sensitivities of 1e-22 W/m$^2$ (5σ), a rough estimate of the confusion limit (Blain *et al*. 2000). Such surveys could be combined with high-resolution images from ALMA to reveal the far-infrared line cooling of the faintest and most distant objects.

*Molecular Hydrogen Line Emission from Primordial Galaxies*

The first objects to form in the early universe gravitationally collapsed from over-dense regions. Energy from these structures was predominantly radiated by molecular hydrogen, because metals were not present to provide more efficient cooling. Molecular hydrogen thus determined the physical size of the earliest objects (M = $10^4$ – $10^6$ solar masses), and their epoch of formation (z = 15 – 100) (Tegmark et al. 1997). The line emission from any one of these objects is faint, but it is possible that a large agglomeration of collapsing clouds might be detectable (Kamaya & Silk 2001).

**Table 1: Measured Line Intensities for M82 and Arp 220**

| | | | M82 | | Arp 220 | |
|---|---|---|---|---|---|---|
| **L/L(solar)** | | | 3.30e10 | | 1.10e12 | |
| **Species** | **Transition** | **L [um]** | **L(line)L(bol)** | **Ref** | **L(line)/L(bolo)** | **Ref** |
| **C I** | 3P 1-0 | 609.1 | 1.60E-06 | stu | 2.30E-06 | gp |
| **C I** | 3P 2-1 | 370.4 | 7.20E-06 | stu | 1.20E-05 | gp |
| **N II** | 3P 1-0 | 205 | 8.80E-05 | pet | | |
| **C II** | 2P 3/2-1/2 | 157.7 | 1.60E-03 | col | 1.26E-04 | luh |
| **O I** | 3P 0-1 | 145.5 | 1.50E-04 | col | < 1.2E-05 | jf |
| **NII** | 3P 2-1 | 121.9 | 2.08E-04 | col | < 3.6E-05 | jf |
| **O III** | 3P 1-0 | 88.4 | 1.05E-03 | col | < 7.2E-05 | jf |
| **O I** | 3P 1-2 | 63.2 | 2.20E-03 | col | -6.80E-05 | jf |
| **N III** | 2P 3/2-1/2 | 57.3 | 4.17E-04 | col | < 2.4E-05 | jf |
| **O III** | 3P 2-1 | 51.8 | 1.26E-03 | col | < 4.8E-05 | jf |
| **Si II** | 2P 3/2-1/2 | 34.8 | 1.12E-03 | fs | 7.73E-05 | gen |
| **S III** | 3P 1-0 | 33.5 | 8.40E-04 | fs | 7.30E-05 | gen |
| **O IV** | 2P 3/2-1/2 | 25.9 | | | < 5.50E-6 | gen |
| **Ne II** | 2P 1/2-3/2 | 12.8 | 1.20E-03 | fs | 7.45E-05 | gen |
| **H2** | 0-0 S(0) | 28.3 | 9.70E-06 | fs | | |
| | 0-0 S(1) | 17.0 | 1.80E-05 | fs | 3.30E-05 | sturm |
| | 0-0 S(2) | 12.3 | 1.94E-05 | fs | | |
| | 0-0 S(3) | 9.7 | 1.20E-05 | fs | | |
| | 0-0 S(4) | 8.0 | 8.42E-06 | fs | | |
| | 0-0 S(5) | 6.9 | 1.38E-05 | fs | 3.30E-05 | sturm |
| **CO** | 1-0 | 2600 | | | | |
| | 2-1 | 1299 | 7.00E-07 | wild | 1.20E-06 | gp |
| | 3-2 | 866 | 2.80E-06 | wild | 2.50E-06 | gp |
| | 4-3 | 649 | | | | |
| | 5-4 | 520 | | | | |
| | 6-5 | 433 | 1.00E-06 | wild | | |
| | 7-6 | 371 | | | | |
| | 8-7 | 324 | | | | |
| | 9-8 | 289 | | | | |

Notes: col = Colbert, J.W., et al. 1999, ApJ 511, 721.
fs = Foester-Screiber, N.M., et al 2001, ApJ 552, 544.
gen = Genzel, R. et al., 1998, ApJ 498, 579.
gp = Gerin, M. & Phillips, T.G., 1998, ApJ 509, L17.
jf = Fisher, J., private communication.
luh = Luhman et al., 1998, ApJ 504, L11.
pet = Petuchowski, S.J. et al., 1994, ApJ 427, 17.
sch = Schilke, J. et al., 1993, ApJ 417, 67.
stu = Stutzki, J. et al., 1997, ApJ 477, 33.
sturm = Sturm, E. et al., 1996, A&A 315, L133.
wild = Wild, W. et al., 1992, A&A 265, 447.

The onset of the first star formation heats the surrounding gas, eventually dissociating $H_2$ and ionizing the IGM by z = 5. During the first phase of star formation and their supernovae, $H_2$ line emission may be bright. For $5 < z < 20$, Ciardi & Ferrera (2001) calculate that the redshifted $H_2$ 6.9 μm (rest wavelength) line should have an observed brightness $10^{-21}$ to $10^{-20}$ W m$^{-2}$, and the 9.7 μm and 17 μm lines should have an observed brightness $10^{-22}$ – $10^{-21}$ W m$^{-2}$ (see Fig. 3).

Finally, $H_2$ lines may be detected in massive systems in the foreground of a FIR luminous distant galaxy in absorption. For example, using a 10 mJy background source, a column density of N($H_2$) = $10^{23}$ cm$^{-2}$, corresponding to a $10^{11}$ solar masses of gas in a 10 kpc diameter, $H_2$ may be detectable (Shibai et al. 2001).

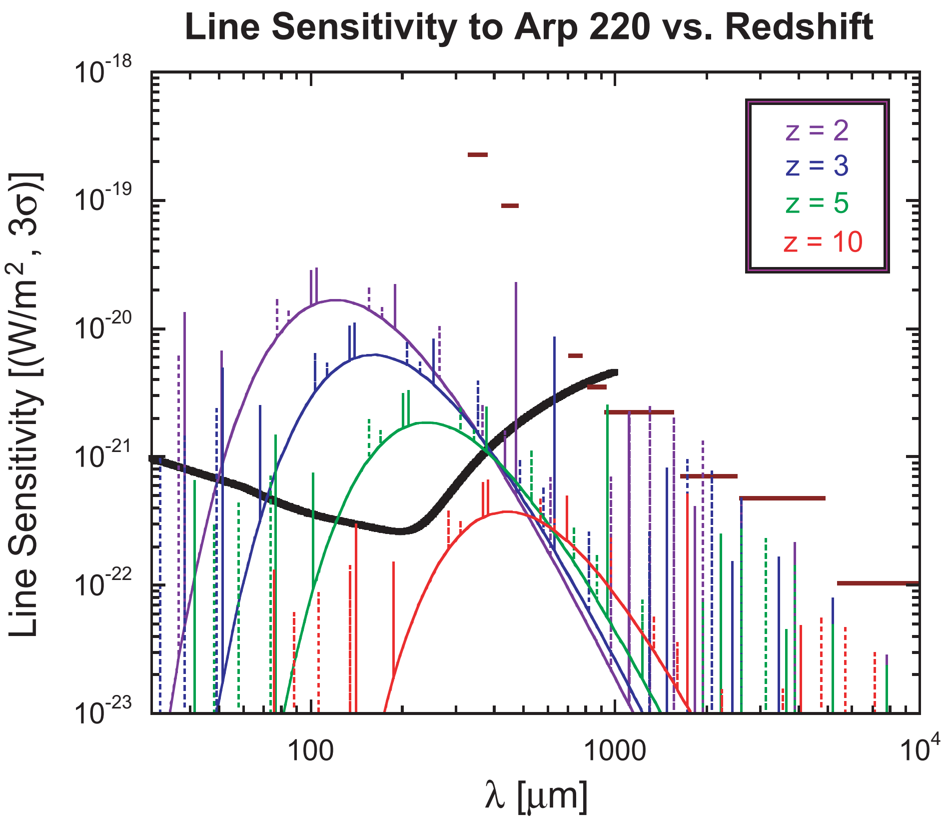


***Figure 4:** The ULIRG (L = 1.1e12 L(solar)) Arp 220 is detectable to z = 10, based on measured (solid) and estimated (dashed) line strengths. We have reduced the continuum emission by 10,000 to emphasize the line intensities. We assume ALMA surveys the atmospheric windows for 300 km/s lines with an instantaneous bandwidth of 4 GHz. Arp 220 is notable for having extremely weak atomic lines, and represents a difficult object for line detection.*

*Local Case-Studies: M82 and Arp 220*

As examples, we take two nearby, well-studied far-infrared luminous galaxies, M82 and Arp 220, and place them at cosmological distance assuming a ΛCDM cosmology ($\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$). In fact, both of these galaxies represent difficult objects for spectroscopy. M82 is a starburst galaxy with prominent atomic and molecular lines. By the standards of the luminous objects detected by SCUBA, M82 is not very luminous. Arp 220 is a ULIRG with very faint atomic line emission. It has the faintest measured $L_{[CII]}/L_{FIR}$ ratio of any ULIRG. The measured line strengths are listed in Table 1.

## CONCLUSIONS

Space-borne far-infrared spectroscopy with direct detectors and a cooled aperture can improve on the sensitivities of planned space missions, but requires significant improvement in the sensitivity and format of direct detectors. Space-borne spectroscopic surveys are complementary to the ground-based ALMA interferometer.

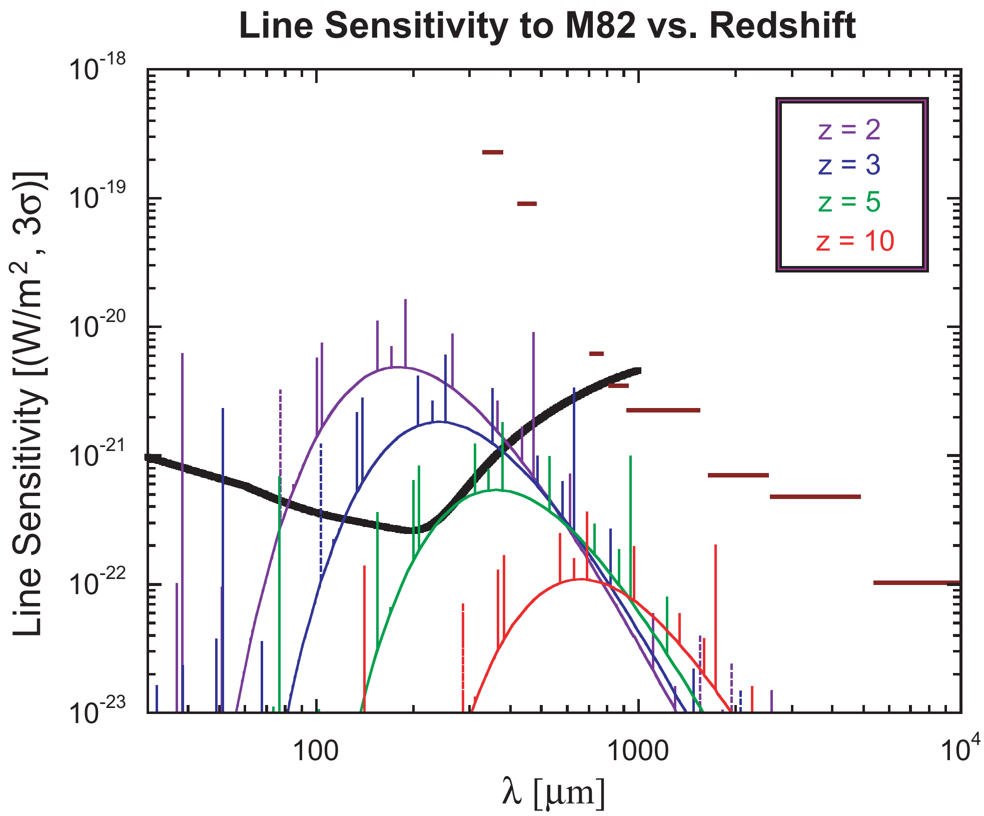


***Figure 5:*** *The starburst galaxy M82 is detectable at z = 5, based on measured (solid) and estimated (dashed) line strengths. We have divided the continuum emission by 1000 to emphasize the line intensities. We assume ALMA surveys the atmospheric windows for 300 km/s lines with an instantaneous bandwidth of 4 GHz. M82 is not an extremely luminous (L = 3.3e10 L(solar)) far-infrared galaxy compared to objects currently being detected by SCUBA at cosmological distances.*

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