KECK HIGH-RESOLUTION SPECTROSCOPY OF OUTFLOWS IN INFRARED-LUMINOUS GALAXIES¹

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ABSTRACT

Several recent studies have determined that large quantities of neutral gas are outflowing from the nuclei of almost all infrared-luminous galaxies. These measurements show that winds in infrared-luminous galaxies play a significant role in the evolution of galaxies and the intergalactic medium at redshifts $z \gtrsim 1$, when infrared-luminous galaxies dominated the star formation rate of the universe. These conclusions rely on moderate-resolution spectra ($\Delta v \gtrsim 65$ km s$^{-1}$) of the Na i D absorption line and the assumption that there are no unresolved, saturated velocity components. For the first time, we present high-resolution spectra ($\Delta v = 13$ km s$^{-1}$) of massive, infrared-luminous galaxies. The five galaxies in our sample are known to host outflows on the basis of previous observations. With the present observations, all Na i D velocity components are resolved with $\tau$(Na i D, $\lambda5896) \leq 6$. The column densities we measure are consistent within the errors with those measured from moderate-resolution observations. This confirms that the mass, momentum, and energy of outflowing gas in infrared-luminous galaxies have been measured correctly by previous studies.

Subject headings: galaxies: ISM — infrared: galaxies — ISM: jets and outflows — ISM: kinematics and dynamics — line: profiles

1. INTRODUCTION

Absorption-line measurements of superwinds in nearby galaxies are now common. Recently, large surveys have performed measurements at moderate spectral resolution of the Na i D doublet to study outflowing gas in infrared-luminous galaxies (Heckman et al. 2000; Rupke et al. 2002, 2005a, 2005b, 2005c; Martin 2005). These surveys show that all infrared-luminous galaxies host massive winds. The detection rate of blueshifted absorption lines is less than 100% in infrared-luminous galaxies, but this does not reflect the actual frequency of occurrence of outflows in these galaxies, which is $\sim 100\%$. Instead, this reflects the fact that the wind does not cover the galaxy completely (Rupke et al. 2005b). Furthermore, the mass, momentum, and energy of the outflowing gas are large and scale with the host galaxy’s star formation rate, luminosity, and mass (Rupke et al. 2005b). Recent mid-infrared observations, as well as radio identifications of submillimeter-selected galaxies, show that luminous and ultraluminous infrared galaxies host most of the star formation in the universe at $z \gtrsim 1$ (Pérez-González et al. 2005; Chapman et al. 2005). The prevalence of massive winds in infrared-luminous galaxies means that these outflows have a significant impact on the evolution of galaxies and the intergalactic medium (Veilleux et al. 2005 and references therein) in the period when most of the stars in the universe are forming.

These conclusions rely on accurate measurements of column densities through profile fitting. However, unresolved, narrow components can cause an underestimate of the true column density of the absorbing gas (Nachmann & Hobbs 1973). The resolution limits of these surveys are $\gtrsim 65$ km s$^{-1}$ FWHM, and the intrinsic velocity profiles are several hundred kilometers per second on average (Heckman et al. 2000; Rupke et al. 2002, 2005b, 2005c; Martin 2005). These profiles are almost certainly superpositions of many components of smaller widths, some of which could be saturated. A handful of dwarf galaxies have been studied at high resolution (10–20 km s$^{-1}$; Lequeux et al. 1995; Sahu & Blades 1997; Schwartz & Martin 2004); the narrowest components in these surveys are still resolved, with FWHM $\gtrsim 25$ km s$^{-1}$. It is necessary to apply the same spectral resolution to a sample of massive, infrared-luminous galaxies, to place limits on the possible errors in column density measurements.

For the first time, we have observed infrared-luminous galaxies at high spectral resolution ($\Delta v = 13$ km s$^{-1}$). We studied the Na i D doublet ($\lambda\lambda5890, 5896$) in four ultraluminous infrared galaxies (ULIRGs; $L_{12}/L_\odot > 10^2$) and one luminous infrared galaxy ($10^{10} < L_{12}/L_\odot < 10^{12}$) with the high-resolution spectrograph on Keck I. Our primary purpose is to find components that may be unresolved by our moderate-resolution spectra (Rupke et al. 2005a, 2005b, 2005c) and confirm or revise our column density measurements.

2. SAMPLE, OBSERVATIONS, AND SPECTRA

We selected five galaxies that represent a variety of interesting Na i D profile types from the parent sample of Rupke et al. (2005a, 2005b, 2005c). One galaxy has a near-systemic component in Na i D with a low-velocity blue wing. Three show broad, relatively smooth profiles with different numbers of components and velocity widths. A fifth possesses an irregular Na i D profile with some redshifted components. Four have infrared luminosities dominated by a starburst (LINER spectral type), and one is a Seyfert 2. Their redshifts range from 0.02 to 0.14. These galaxies and their properties are listed in Table 1.

We observed them during one community-access night (2003 December 27 UT) at the Keck I telescope using the High Resolution Spectrograph (HIRES; Vogt et al. 1994). We used a different set-up for each galaxy, in order to optimally align the Na i D feature and prominent emission lines on the detector. The slit size was 17′′ × 14′′ (the D4 decker), yielding a resolution of $R \sim 23,000 = 13$ km s$^{-1}$. The old 2K x 2K CCD was in use, as well as the GG-475 filter and red collimator.

¹ The observations reported here were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among Caltech, the University of California, and NASA. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.
TABLE 1

| Name          | \( z \)      | Type | \( L_{\text{IR}} \) | \( \log L_{\text{IR}} \) | P.A. | Reference |
|---------------|--------------|------|---------------------|--------------------------|------|-----------|
| F02437+2122   | 0.0233       | L    | 11.10              | 4800                     | 55   | 1         |
| F03250+1606   | 0.1290       | L    | 12.13              | 9000                     | 0    | 2         |
| F05189-2524   | 0.04275a     | S2   | 12.11              | 3600                     | 0    | 2         |
| F09039+0503   | 0.1252       | L    | 12.10              | 9600                     | 0    | 2         |
| F10378+1108   | 0.1363       | L    | 12.32              | 6300                     | 0    | 2         |

Notes.—Col. (1): IRAS Faint Source Catalog label. Col. (2): Heliocentric redshift (Rupke et al. 2005b). Col. (3): Optical spectral type (Rupke et al. 2005b, 2005c). \( L_{\text{IR}} \) LINER, S2 Seyfert 2. Col. (4): Logarithm of the infrared luminosity. Col. (5): Total exposure time. Col. (6): Position angle of observation slit, in degrees east of north. Col. (7): References.

* Our high resolution allows us to separate the Mg \( b \) lines in this galaxy. The resulting redshift is the most accurate to date (\( z_p = 0.04271 \pm 0.00003 \)) and matches \( z_p = 0.04275 \pm 0.00007 \) that determined from CO data (\( z_p = 0.00007 \) and low-ionization emission lines (\( z = 0.04271 \pm 0.00003 \)) within the errors.

References.—(1) Kim et al. 1995; Veilleux et al. 1995; Sanders et al. 2003; (2) Kim & Sanders 1998; Veilleux et al. 1999.

Data reduction was performed with the MAKEE² software package.

The spectra of the Na \( \lambda \lambda 5890, 5896 \) doublet and He \( \lambda 5876 \) emission line in the rest frame of the galaxy.

3. MODERATE VERSUS HIGH RESOLUTION

The moderate- and high-resolution profiles are almost identical. At a resolution of 13 km s\(^{-1}\), these galaxies have remarkably smooth Na \( \lambda \lambda 5890, 5896 \) profiles. There are some high-frequency variations in the spectra that would appear to be marginally significant based on the 1 \( \sigma \) Poisson errors. These cannot be stellar absorption lines; their widths of tens of kilometers per second or less are inconsistent with the much larger stellar velocity dispersions of ULIRGs (Tacconi et al. 2002). If they were due to variation in the absorbing gas properties, they would not appear in the continuum, which they do. We conclude that these variations are due to underestimated noise (e.g., flat-fielding errors, fringing).

To fit the data, we increase the number of components until the properties of one or more components becomes unconstrained in Monte Carlo simulations (Rupke et al. 2005a). Using more components causes instabilities in the solution, while using fewer components provides an unacceptable fit. We find that in every case but one (F02437+2122) the same number of components is required at both resolutions. A close examination of Figure 1 shows that corresponding components are, in general, similar in velocity and shape at different resolutions. One difference is that high resolution gives more sensitivity to high optical depths, simulations. The column densities are then computed from the fitted parameters. Table 2 lists the fit parameters and column densities of each velocity component.

Fitting only a few components (2–4) does a good job of matching the profile shapes. There are a few places in the spectra where the data and model do not match perfectly, but these can be attributed to small deviations from Gaussianity in the optical depth profile or a varying covering fraction. Power spectra of the residuals from the fit show nothing significant.

![Figure 1](image-url)
which allows us to relax the parameter boundaries imposed on the moderate-resolution observations \( \tau(L5896) \leq 5 \). Despite this, we fit only one high-resolution component with \( \tau > 5 \).

A more quantitative test of the differences between high- and moderate-resolution components confirms these similarities on average. We find that the median velocity difference per component is within a few kilometers per second of zero. The column densities in the high-resolution data are lower by 45% on average (and do not change by more than a factor of 3). The outflowing masses, momenta, and energies decrease by 20% on average. These results are consistent within the errors with those from moderate resolution spectroscopy. We thus demonstrate that the conclusions of recent surveys (Heckman et al. 2000; Rupke et al. 2002, 2005a, 2005b; Martin 2005) are robust to increases in spectral resolution.

Some noticeable differences exist between the moderate- and high-resolution data of F02437+2122, including changes in profile depth and shifts in wavelength. These are likely due to the different aperture sizes of the two observations: the high-resolution extraction aperture subtends 4 arcsec\(^2\), while the moderate-resolution aperture subtends 12 arcsec\(^2\). (The differences in aperture for the other four galaxies are negligible.) The larger aperture may probe a different overall velocity distribution of gas (since we observe rotation in Na i D in this galaxy in the moderate-resolution data) and include more continuum light.

In one galaxy, F90039+0503, we resolve a narrow component that was unresolved by our moderate-resolution spectra. This component is redshifted from systemic by 180 km s\(^{-1}\) and has a (resolution-corrected) FWHM of 32 km s\(^{-1}\). The FWHM from the moderate-resolution data is larger by 50%. This component is also observed in Ca ii K at moderate resolution. Since this component is infalling and has a small velocity width, and given the origin of most ULIRGs in a major merger (e.g., Murphy et al. 1996; Clements et al. 1996; Farrah et al. 2001; Bushouse et al. 2002; Veilleux et al. 2002), we suggest that this component represents tidal debris falling back on to the galaxy.

### 4. PHYSICAL MODEL

What motions cause the line widths we observe? If clouds or filaments entrained in these outflows are dominated by internal thermal motions, we should not expect to resolve them. (The thermal line width for Na is 2.5 km s\(^{-1}\) in a \( T = 10^4 \) K gas.) However, the smallest velocity FWHM we observe is a factor of 10 above this limit and twice the spectral resolution. Individual velocity components must therefore be a superposition of many clouds with different central velocities. The different velocities of these clouds are due to the motions of the wind that spread the clouds over both velocity space and real space, as seen in many simulations and observations. Fortunately, such an ensemble can often be properly treated as a single component as we have done (Jenkins 1986).

We observe only two components that have a FWHM smaller than 100 km s\(^{-1}\). Dwarf starbursts have many components with FWHM < 100 km s\(^{-1}\), but the velocities of their outflows are smaller than in infrared-luminous galaxies (Rupke et al. 2002, 2005b; Schwartz & Martin 2004; Martin 2005). The larger average line widths in ULIRGs (FWHM = 330 km s\(^{-1}\); Rupke et al. 2005b) than in dwarf galaxies (40 km s\(^{-1}\); Schwartz & Martin 2004) are a consequence of the larger energy reservoirs available to power the outflows in infrared-luminous galaxies (Rupke et al. 2005b).

A near-field example of cloud ensembles resolved into individual components are the high-velocity clouds (HVCs) in our Galaxy. Very high resolution (2 km s\(^{-1}\)) Na i D observations of intermediate- and high-velocity clouds resolve structures with line widths down to the resolution limit, embedded in blended spectral structures as wide as 20 km s\(^{-1}\) (Lehner et al. 1999). A width of 2 km s\(^{-1}\) is consistent with the thermal line width of Na at \( T = 10^3 \) K but implies some turbulent broadening (or accumulation of smaller cloudlets) if the temperature is lower than this. Because of their proximity, HVC cloudlets are known to be distinct not only in velocity space but also in real space. Wakker & Schwarz (1991) find that HVCs, which have neutral hydrogen line widths of tens of kilometers per second when observed over large angular scales, have much smaller line widths (a few kilometers per second) on small angular scales (1°).

Envisioning the Na i D absorption in infrared-luminous galaxies as an ensemble of small clouds, we can make an estimate of the number of clouds present in the line of sight. We compute this number by dividing the total column density in an average

### Table 2: Outflow Component Properties

| Name               | \( \lambda_{D} \) (Å) | \( \Delta \lambda \) (km s\(^{-1}\)) | \( b \) (km s\(^{-1}\)) | \( \tau_{i} \) | \( C_{f} \) | \( N(\text{Na} i) \) (cm\(^{-2}\)) | \( N(\text{H}) \) (cm\(^{-2}\)) |
|--------------------|------------------------|--------------------------------------|--------------------------|----------------|----------|----------------------------------|--------------------------|
| F02437+2122       | 6032.33                | -133 ± 4                             | 222 ± 7                  | 0.48±0.02      | 0.66±0.03 | 13.58                            | 20.88                    |
| F03250+1606       | 6650.46                | -355 ± 5                             | 234 ± 12                 | 6.25±0.24      | 0.37±0.07 | 13.94                            | 21.24                    |
| F05189-2524       | 6140.41                | -452 ± 3                             | 429 ± 7                  | 0.44±0.01      | 0.30±0.01 | 13.83                            | 21.19                    |
| F09039+0503       | 6647.86                | -89 ± 0                              | 103 ± 1                  | 1.63±0.05      | 0.20±0.01 | 13.78                            | 21.13                    |
| F10378+1108       | 6686.37                | -673 ± 15                            | 760 ± 40                 | 0.19±0.05      | 0.48±0.13 | 13.72                            | 21.09                    |
| F6954.75          | -265 ± 17              | 264 ± 34                             | 0.76±0.12                | 0.10±0.04      | 13.85    | 21.22                            |                           |
ensemble (velocity component) by the column density of an average cloud (each computed using eq. [10] of Rupke et al. 2005a). For a cloud, we assume an average \( \tau_i = 0.1 \) and \( b_{v_i} = 2 \) km s\(^{-1}\) based on observations of high-velocity clouds (Lehner et al. 1999), and for ULIRGs we measure \( \tau_{en} (5896) = 0.9_{-0.6}^{+0.8} \) and \( b_{en} = 200_{-80}^{+170} \) km s\(^{-1}\) (Table 1 of Rupke et al. 2005b). The average number of clouds in a ULIRG velocity component is then 900 clouds, with a \( 1 \sigma \) range of 150–4500 clouds. The number (230) of warm ionized clouds or resolved structures seen in high-resolution Hubble Space Telescope observations of NGC 3079, a well-known local galaxy hosting a superwind (Cecil et al. 2001), falls in the low end of this range. We would expect our estimate for ULIRGs to be on average larger, given that the cloud properties we assume are based on observations of very small structures in the Galaxy.

5. SUMMARY

We have performed observations at very high spectral resolution (\( \Delta \nu = 13 \) km s\(^{-1}\)) of the Na i D doublet in five infrared-luminous galaxies in order to confirm or deny measurements made at moderate resolution. We find that the resulting column densities are consistent within the errors with previous measurements. Thus, the results of previous and forthcoming studies of the Na i D feature are reliable (e.g., Heckman et al. 2000; Rupke et al. 2002, 2005a, 2005b, 2005c; Martin 2005). They find that superwinds in infrared-luminous galaxies are massive and occur with high frequency. The impact of these winds on galaxy evolution and the intergalactic medium, especially at high redshifts (\( z \approx 1 \)), is likely to be substantial.

Our observations of the Na i D doublet do not clearly resolve any new outflowing components in these galaxies. One redshifted component is newly resolved; we associate this component with tidal debris from a merger. These results are consistent with the lack of narrow components (FWHM < 25 km s\(^{-1}\)) in nearby dwarf starbursts (Schwartz & Martin 2004). Our data are consistent with a model in which an absorber is composed of many clouds (~1000) that fill the line of sight and form a large ensemble that enters our fits as a single absorbing “component.” Na D observations of high-velocity clouds in our Galaxy resolve cloudlets with an average width of FWHM = 3 km s\(^{-1}\), and these cloudlets may be similar to clouds that exist in superwinds. However, motions that separate the clouds in velocity and real space clearly dominate the line width of an individual velocity component (FWHM = 250–350 km s\(^{-1}\)).

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