The Interstellar Medium of IRAS 08572+3915 NW: $\text{H}_3^+$ and Warm High Velocity CO$^{1,2}$

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ABSTRACT

We confirm the first detection of the molecular ion $\text{H}_3^+$ in an extragalactic object, the highly obscured ultraluminous galaxy IRAS 08572+3915 NW. We also have detected absorption lines of the fundamental band of CO in this galaxy. The CO absorption consists of a cold component close to the systemic velocity and warm, highly blueshifted and redshifted components. The warm blueshifted component is remarkably strong and broad and extends at least to -350 km s$^{-1}$. Some analogies can be drawn between the $\text{H}_3^+$ and cold CO in IRAS 08572+3915 NW and the same species seen toward the Galactic center. The profiles of the warm CO components are not those expected from a dusty torus of the type thought to obscure active galactic nuclei. They are probably formed close to the dust continuum surface near the buried and active nucleus and are probably associated with an unusual and energetic event there.

Subject headings: galaxies: active — galaxies: individual (IRAS 08572+3915) — galaxies: ISM — infrared: galaxies — line: profiles — molecular processes

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1. Introduction

Ultraluminous infrared galaxies (ULIRGs) have been extensively studied at all wavelengths from the radio to X-ray in order to probe the nature of the energy source - starburst and/or active galactic nucleus (AGN). Numerous investigators have concluded that ULIRGs are mainly found in interacting systems (e.g., Sanders & Mirabel 1996; Veilleux, Kim, & Sanders 2002, and references therein). However, in the many cases where the nuclear regions are heavily obscured it is still unclear whether their huge luminosities are the result of greatly enhanced nuclear star formation, or greatly enhanced accretion by a central black hole, or both. Infrared spectroscopy potentially has an important role to play in this investigation, as it can probe regions close to the nucleus at high angular resolution and detect diagnostics unique to each phenomenon, as well as discern the nature of the interstellar medium of the ULIRG more distant from the nucleus. Recent observations using this technique include the measurements of broad line regions and coronal lines, which are signposts of AGNs, in several ULIRGs (Veilleux, Sanders, & Kim 1999; Murphy et al. 2001), the detection of interstellar aromatic hydrocarbon features and hydrogen recombination lines indicative of massive star formation (Imanishi & Dudley 2000; Soifer et al. 2002; Dannerbauer et al. 2005) in a partially intersecting set of ULIRGs, and most recently and perhaps most remarkably, the discovery of CO in dense and warm gas close to the central luminosity source of the z=0.327 ULIRG, IRAS F00183-7111 (Spoon et al. 2004).

H$_3^+$, the highly reactive molecular ion upon which interstellar gas phase chemistry is based (Herbst & Klemperer 1973; Watson 1973), is a potentially useful infrared spectroscopic tool for studying the interstellar gas in distant galaxies. It is important observationally for understanding both dark and diffuse interstellar clouds (Geballe 2000). In both types of clouds it is produced following cosmic ray ionization of H$_2$ to H$_2^+$, which quickly reacts with H$_2$ to form H$_3^+$. The steady state abundance of H$_3^+$ is very low, because it is destroyed readily in dark clouds by reactions with neutral molecules (principally CO) and atoms (mainly O) and even more readily in diffuse clouds by dissociative recombination with electrons, which, due to the photoionization of carbon, are much more abundant than in dark clouds. The absorption strengths of H$_3^+$ lines provide basic information on the cloud dimensions and environment, in addition to temperature. The observed column density of H$_3^+$ can directly yield the product of the distance through the cloud and the cosmic ray ionization rate in the cloud. This is because unlike most other molecules, the number density of H$_3^+$ in a cloud is a constant that depends only on the ionization rate of H$_2$ and whether the cloud is dark or diffuse. This unusual property of H$_3^+$ comes about because its creation rate per unit volume is proportional to the first power of the cloud density, rather than to the square.

The detection of strong H$_3^+$ absorption toward the center of the Galaxy (Geballe et
al. 1999) suggests that it also should be possible to detect H$_3^+$ in the interstellar medium of suitable external galaxies - those with sufficiently bright and compact sources of infrared continuum radiation and large column densities of interstellar molecular gas along their lines of sight. One of the most promising galaxies for an H$_3^+$ search is the ULIRG, IRAS 08572+3915. Images at several wavelengths of this interacting pair of galaxies can be found in Evans et al. (2002). The 3.4 µm interstellar hydrocarbon absorption observed by Wright et al. (1996) and Imanishi & Dudley (2000) (also see Fig 1, this paper) in the northwest component of this merging galaxy pair is deeper than that observed toward the Galactic center. In the Galaxy this feature signifies extinction by dust in diffuse clouds. The 10 µm silicate absorption toward IRAS 08572+3915 NW (Dudley & Wynn-Williams 1997; Spoon et al. 2006a) also is among the strongest detected. In addition IRAS 08572+3915 NW possesses intense CO line emission at millimeter wavelengths (Sanders et al. 1989; Evans et al. 2002). Thus extensive columns of diffuse and dense gas exist in front of the nuclear infrared source of IRAS 08572+3915 NW, which may contain a buried AGN (Dudley & Wynn-Williams 1997; Imanishi & Dudley 2000), although this interpretation has been contested (Arribas, Colina, & Borne 2000).

Here we report confirmation of the detection of H$_3^+$ in IRAS 08572+3915 NW reported by Geballe (2001). To gain additional information about the interstellar medium of this galaxy we also obtained a spectrum of it in the region of the fundamental band of carbon monoxide. This spectrum reveals both a cold interstellar component, possibly associated with some of the gas containing the detected H$_3^+$, and an unusual warm and dense component superficially similar to that observed toward IRAS F00183-7111 by Spoon et al. (2004). Here, however, the CO band is resolved into individual lines and the lines themselves are velocity-resolved, revealing remarkably broad and high speed components.

A data log of the observations reported below is provided in Table 1. In all cases data reduction was straightforward, involving removal of bad frames, extraction of spectra from coadded 2D spectral images, wavelength calibration using arc lamps and telluric absorption lines, despiking, division by a telluric standard star observed at close to the same airmass and reduced in a similar fashion, and flux calibration using the observed or predicted flux density of the standard.
2. Observations and Results

2.1. H$_3^+$

An initial search for H$_3^+$ in IRAS 08572+3915 NW was made in 1998 December at the United Kingdom Infrared Telescope (UKIRT) with the use of the facility spectrograph CGS4 (Mountain et al. 1990), employed at a resolving power of 1500 and covering 3.4-4.0 $\mu$m. No H$_3^+$ lines were detected. This spectrum is shown in Fig. 1, because it is a better quality spectrum of the redshifted 3.4 $\mu$m hydrocarbon absorption feature in IRAS 08572+3915 NW than those published to date (Imanishi & Dudley 2000; Mason et al. 2004). The spectrum also illustrates the difficulty of detecting weak lines from the ground at medium spectral resolution in the thermal infrared region.

In December 2000 a 3.82-3.98 $\mu$m spectrum of IRAS 08572+3915 NW was obtained at UKIRT, with CGS4 configured to give a higher resolving power of 6000. The spectrum covered the wavelength range of three lines of H$_3^+$ from the lowest lying ortho and para levels. These are the R(1,1)$^u$ - R(1,0) doublet at 3.66808 $\mu$m and 3.66852 $\mu$m (separated by 36 km s$^{-1}$), whose mean wavelength is redshifted to 3.8822 $\mu$m and the R(1,1)$^l$ singlet at 3.71548 $\mu$m redshifted to 3.9321 $\mu$m. We use z=0.0583, which was determined from the CO pure rotational 1-0 line (Evans et al. 2002) and is probably accurate to better than 0.0001 (30 km s$^{-1}$), as the nominal systemic redshift and express all wavelengths in vacuo. The relevant portion of the spectrum is shown at the top of Fig. 2. Statistically significant absorption features were observed at the expected wavelengths of the lines, indicating that the molecular ion had been detected (Geballe 2001). The H$_3^+$ search was repeated in 2002 and 2004 at the Subaru Telescope using its Infrared Camera and Spectrograph (IRCS) (Tokunaga et al. 1998; Kobayashi et al. 2000) at resolving powers of 10,000 and 5,000. These data, each summed in 0.0006 $\mu$m ($\sim$50 km s$^{-1}$) wide bins to match the UKIRT point spacing, also are shown in Fig. 2 and, except for the singlet in the 2004 spectrum, also contain modest signal-to-noise-ratio detections of these lines. In the 2004 data the signal near the wavelength of the singlet is depressed as expected, but it is also depressed at adjacent wavelengths.

The transmission spectrum of the earth’s atmosphere in the 3.86-3.95 $\mu$m interval contains about fifty narrow and roughly evenly spaced absorption lines from high altitude N$_2$O. In unratioed spectra with the above binning the strongest of these are 20% deep. Any effects due to non-cancellation of these lines would result in systematic features of comparable strengths at many wavelengths in the ratioed spectra. No evidence for any such features is present in any of the individual spectra. The broad and weak emission bumps centered near 3.908 $\mu$m in the spectra are due to absorption by HI 15-6 in the spectra of the A dwarf telluric standards.
The mean of the three spectra is shown near the bottom of Fig. 2. In it the detection of the doublet is convincing, whereas that of the singlet is marginal (at about $3\sigma$). Relative to the systemic velocity, the centroids of the doublet and the singlet correspond to LSR velocities of $-50 \pm 30$ km s$^{-1}$ and $+10 \pm 50$ km s$^{-1}$, respectively. Thus there is some disagreement in the velocities of the two features, but it is within the uncertainties, which are due to possible errors in the wavelength calibration, the uncertain relative contributions of the components of the doublet, and the noise in the spectrum. The uncertainty in the wavelength scale is determined largely by the UKIRT spectrum, and conservatively is 10 km s$^{-1}$. The uncertainty in the centroid of the doublet depends on the width and signal-to-noise ratio of the feature and on the relative contributions of the two lines (separated by 36 km s$^{-1}$, which is roughly 1:1 in Galactic dark clouds (McCall et al. 1999) and toward the Galactic center (Oka et al. 2005). The uncertainty due to feature’s profile and signal-to-noise ratio is about 20 km s$^{-1}$ whereas reasonable variation in the ratio of the doublet’s components translates into an uncertainty of about 5 km s$^{-1}$ in the centroid. Thus the overall uncertainty in the velocity centroid of the doublet is about 30 km s$^{-1}$. For the marginally detected singlet the uncertainty in the centroid due to the noise is at least the point spacing which is 46 km s$^{-1}$ (this can be seen by comparing the centroids of the UKIRT 2000 and Subaru 2002 spectra), giving an overall uncertainty in the velocity centroid of roughly 50 km s$^{-1}$ for that line.

Although the moderate discrepancy in velocities suggests the possibility that the weak absorption at 3.932 $\mu$m is a noise fluctuation and that the much stronger 3.882 $\mu$m absorption feature has an identification other than H$_3^+$, we believe that this is unlikely. First, we have found no other viable candidate for the 3.882 $\mu$m absorption other than H$_3^+$. Second, in the numerous Galactic sources in which this doublet has been detected there is no evidence of contamination of the doublet by other lines. Third, we expect to detect H$_3^+$ at roughly this strength toward IRAS 08572+3915 based on the heavy obscuration of the nuclear source and the evidence for a high column density of diffuse interstellar gas and by analogy to the Galactic center. Finally, the radial velocity of the 3.88 $\mu$m absorption, if due to H$_3^+$, is the same (to well within the uncertainties) as that of the peak absorption by cold CO discussed in the next subsection.

The equivalent widths of the two features are given in Table 2. Their uncertainties are based on average point-to-point fluctuations in the spectrum near the lines. The 3.88 $\mu$m doublet has more than three times the equivalent width of the singlet. Using the standard equations relating column density to equivalent width (Geballe & Oka 1996), we derive column densities of $1.8 \pm 0.6 \times 10^{15}$ cm$^{-2}$ in the (1,1) para level and $2.6 \pm 0.6 \times 10^{15}$ cm$^{-2}$ in the (1,0) ortho level. The most likely values yield a formal excitation temperature of 100 K, but this result is highly uncertain mainly due to the large uncertainty in the equivalent width of the singlet. At densities typical of molecular clouds the total H$_3^+$ column density
is the sum of the above values, $4.4 \times 10^{15}$ cm$^{-2}$. If the temperature is significantly higher than 100 K and the clouds are diffuse, a few higher levels can be significantly populated and the total column density of H$_3^+$ could be higher, as shown by Oka & Epp (2004). In the Galactic Center, where much of the H$_3^+$ is in clouds at temperatures of $\sim 250$ K, the total column density of $4.3 \times 10^{15}$ cm$^{-2}$ is one-fourth greater than the sum of the column densities in these lowest ortho and para levels (Oka et al. 2005).

### 2.2. CO

Figure 3 shows the 4.90-5.05 $\mu$m spectrum of IRAS 08572+3915 NW observed at a resolving power of 7500. The spectrum is noisy and several intervals within it are unrecoverable due to strong telluric absorption lines. However, it is clear that the spectrum contains strong and broad absorption lines of the fundamental band of CO, stretching across the entire observed interval. Indeed the lines are so broad that in some portions of the spectrum it is unclear if continuum gaps exist between them. The spacing of lines of the 1-0 band of CO is typically 550 km s$^{-1}$. The apparent elevation of the continuum near 4.92 $\mu$m might be due to H I Pa $\beta$ which is redshifted to 4.925 $\mu$m, although the line appears to be considerably wider than that of shorter wavelength infrared H I recombination lines observed by Goldader et al. (1995) and Veilleux, Sanders, & Kim (1999).

The centroids of the CO lines in IRAS 08572+3915 NW are considerably blueshifted from the central wavelengths determined from the systemic redshift of the galaxy. Moreover, although the signal-to-noise ratio of the spectrum is low, careful examination of Fig. 3 suggests that the lines from the lower rotational levels are broader than those from high J. To better test whether a separate velocity component is present in the low J lines, we have coadded the spectra of the R(1), R(2), and P(1) lines as well as those of the P(6), P(8), and P(11) lines, lines least affected by telluric absorption. These average low J and high J spectra are compared in Fig. 4. The low J line profiles have two strong absorption maxima, at approximately $-50 \pm 25$ and $-150 \pm 25$ km s$^{-1}$ relative to the systemic velocity, whereas only a single strong absorption maximum, at $-160 \pm 25$ km s$^{-1}$, is present for the high J profiles. Thus, roughly speaking there is a warm blueshifted CO absorption component extending roughly from 0 to $-350$ km s$^{-1}$ and a cold component centered near 0 km s$^{-1}$, at approximately the same radial velocity as the H$_3^+$ lines. A warm redshifted component, that appears to be present in the mean high J profile in Fig. 4, has recently been confirmed by Shirahata et al. (2006). In the UKIRT spectrum it is centered at $+100 \pm 30$ km s$^{-1}$ and is considerably weaker and narrower than the other two components.

There is little or no evidence for CO absorption or emission from vibrationally excited
states. The v=2-1 R(6) transition (4.939 \( \mu \text{m} \)), which occurs at the CO v=1-0 band center corresponds to a marginal depression in the continuum between the strong CO 1-0 lines. However, the continuum levels between the 1-0 lines at 5.02-5.06 \( \mu \text{m} \), where the v=2-1 line wavelengths lie midway between the 1-0 lines, are comparable to the levels between 1-0 lines at 4.96-4.99 \( \mu \text{m} \), where the 2-1 line wavelengths coincide with the 1-0 lines.

The characteristic CO temperatures and column densities are difficult to determine accurately from the narrow spectral range observed. Strong blueshifted absorption lines are present at all observed J levels (up to 12), implying that the warm blueshifted CO component is close to or in LTE, and that either the blueshifted portions of the medium J lines are optically thick or the blueshifted gas has a range of temperatures. It appears that the line from the highest J level observed, the P(12) line, is somewhat weaker than the lines from lower levels. This and the estimated strength of the R(0) and P(1) blue components allow us to crudely and tentatively estimate the mean temperature of the warm blueshifted component to be 200 (+100, -50) K. Insufficient information is available to estimate the temperature of the weak redshifted component, but it may be warmer than the blueshifted component.

Assuming an isothermal optically thin slab in this temperature range, the column density of the warm blueshifted component is \( 2 \times 10^{18} \text{ cm}^{-2} \), with an uncertainty of a factor of two. However, it is almost certainly an oversimplification to regard the warm absorbing gas as isothermal and optically thin at all velocities. As discussed in section 3.2, the profile is probably made up of spatially separated velocity components. If each of these is absorbing along a different line of sight to a different location on the continuum source, the actual line optical depths are considerably greater than in the above estimate. A column density an order of magnitude higher than the above value would not be surprising.

This argument may also apply to the column density of the cold low velocity absorption component. Based on its strength and small number of rotational levels that are populated, the column density of this component is probably several times less than that of the warm blueshifted component. The column density of the warm redshifted component is even less. Assuming \([\text{CO}]/[\text{H}_2] = 1.5 \times 10^{-4}\) (Lee, Bettens, & Herbst 1996) the lower limit on the hydrogen column density associated with the observed CO (assuming the lines are optically thin) is \( N(\text{H}_2) \approx 1.5 \times 10^{22} \text{ cm}^{-2} \). By comparison, from the peak optical depth of 4.2 in the 10 \( \mu \text{m} \) silicate absorption feature (Spoon et al. 2006a) and using \( A_V/\tau_{\text{sil}} = 17.5 \) (Roche & Aitken 1984; Rieke & Lebofsky 1985) and \( N_H = 1.9 \times 10^{21} \text{ cm}^{-2} \text{ mag}^{-1} \), we obtain \( N(\text{H}_2) = 7 \times 10^{22} \text{ cm}^{-2} \), which is also a lower limit because of the possibility of radiative transfer effects and/or foreground silicate emission.
3. Discussion

3.1. Low velocity H$_3^+$ and CO

The velocity of the H$_3^+$ is close to the systemic velocity of IRAS 08572+3915 NW, as indicated in Fig. 2. Although the absorption lines of H$_3^+$ appear fairly simple in shape, the low signal-to-noise ratio and low resolution could be masking many details. Figure 2 includes the spectrum toward the Galactic center source GCS3-2 recently observed at 6 km s$^{-1}$ resolution by Oka et al. (2005), but shown here with the same binning as the IRAS 08572+3915 NW spectra. Oka et al. (2005) found that the spectrally resolved profile of GCS3-2 has a full width at zero intensity (FWZI) of 150 km s$^{-1}$ and at least six discrete velocity components, from both diffuse and dark clouds, some within a few tens of parsecs of the center and some in distant spiral arms. The H$_3^+$ absorption line profiles towards IRAS 08572+3915 NW could be similarly complex.

The presence of a strong 3.4 $\mu$m interstellar feature suggests that a considerable fraction of the interstellar molecular gas along the line of sight toward the nuclear continuum source of IRAS 08572+3915 NW is in diffuse clouds, as is the case towards the Galactic center (Whittet et al. 1997). If so and assuming that the total column density of H$_3^+$ is not greatly different from the sum of the column densities in the lowest ortho and para levels, $4.4 \times 10^{15}$ cm$^2$, we can estimate the column length of absorbing H$_3^+$ from its steady state density in diffuse clouds. The value of $n$(H$_3^+$) depends on the assumed cosmic ray ionization rate, $\zeta$. Assuming the previously canonical value of $\sim 1 \times 10^{-7}$ cm$^{-3}$ s$^{-1}$ for $n$(H$_3^+$) in diffuse clouds (McCall et al. 1998; Geballe et al. 1999) obtained if $\zeta = 3 \times 10^{-17}$ s$^{-1}$, the derived length of the column containing H$_3^+$ in IRAS 08572+3915 NW is $\sim 10$ kpc, which clearly is unrealistically long. A similar unreasonably high result is obtained for the Galactic center (Geballe et al. 1999). Using the 40 times higher cosmic ray ionization rate found in one galactic diffuse cloud, but suspected of existing in many or all such clouds (McCall et al. 2003) reduces the pathlength to a still high, but more reasonable 300 pc. In the Galactic center Oka et al. (2005) have found that the ionization rate is even several times higher than this value. If conditions in IRAS 08572+3915 NW are similar, the pathlength then would be reduced to less than 100 pc. If instead, all of the H$_3^+$ were found in dense clouds the pathlength though them would be $\sim 10$ pc, but it then would be difficult to explain the absence of H$_3^+$ in the diffuse clouds that produce the strong 3.4 $\mu$m feature. Moreover, the extinction through the dense cloud material to the continuum source would be unrealistically high, $\sim 1000$ mag, based on the rough Galactic ratio $N$(H$_3^+$) to $A_V$ of $3.6 \times 10^{12}$ cm$^{-2}$ mag$^{-1}$ as reported by Oka et al. (2005). Thus we conclude that the bulk of the observed H$_3^+$ is located in diffuse molecular gas.
The absorption lines of H$_3^+$ and the cold CO have similar velocity ranges. However, as in the case of the Galactic center (Oka et al. 2005), they probably do not arise in all of the same clouds. The CO abundance in diffuse clouds is only one percent of the carbon abundance, whereas in dense clouds almost all carbon is in CO. Thus the absorption by cold CO must occur primarily in dense clouds, whereas, as argued above, the lines of H$_3^+$ are probably formed mainly in diffuse clouds. The present CO data do not allow much to be inferred about the dense clouds, although they do suggest from the width of the cold component that, as in the case of the Galactic center, there are several of them along the line of sight.

### 3.2. High velocity CO

The discovery of high velocity CO features is the most striking result of this paper. Clearly there is no physical relation whatsoever between the dominant blueshifted CO absorption and the H$_3^+$. This is because (1) highly blueshifted velocities are not seen in the H$_3^+$ lines, despite the large CO column density in that component, and (2) the column density of blueshifted H$_3^+$ must be very low, because the length of the column of blueshifted CO is very short, as discussed below.

The existence in the high velocity gas of strong CO lines from levels as high as J=12 implies that the CO rotational population is maintained in LTE to at least that level. Using our crude determination of 200 K for the kinetic temperature and equating the Einstein A coefficient for the J=12-11 transition (equation 1 in Thompson (1973)) to the collisional excitation rate assuming a cross section for collisional excitation by H$_2$ of 1 $\times$ 10$^{-15}$ cm$^{-2}$ (e.g., McKee et al. 1982), we estimate that the gas density $n$(H$_2$) must be at least 3 $\times$ 10$^6$ cm$^{-3}$. For [CO]/[H$_2$] = 1.5 $\times$ 10$^{-4}$ (Lee, Bettens, & Herbst 1996), the lower limit to the observed warm CO column density of 2 $\times$ 10$^{18}$ cm$^{-2}$ implies that the overall column length of warm CO is less than 0.001 pc, or less than 0.01 pc for an order of magnitude higher CO column density. The H$_3^+$ column density expected in such short column lengths would be undetectable.

Confinement of the observed wide range of blueshifted velocities to a single clump of gas that is this thin and is detached from the continuum source is inconsistent with the observations. Collisions between portions of the gas in the clump at relative velocities of more than ten kilometers per second would heat the gas significantly above the observed temperatures, and collisions at more than several tens of kilometers per second would dissociate even the CO. Yet there is no evidence in our spectra for the CO being vibrationally excited. Thus if the absorbing gas is detached it must be composed of numerous well separated thin sheets.
of dense gas each of which contains a narrow range of velocities.

It is simpler to account for the wide range of blueshifted velocities if the line-forming CO is located on the outer surface of an expanding, more-or-less spherical, optically thick continuum source. In such a geometry a range of absorption velocities would be present, from near zero near the edges of the source to most highly blueshifted at the center. This simple model implies an expansion velocity of \( \sim 350 \text{ km s}^{-1} \) and a column much higher than the upper in section 2.2, as discussed earlier.

This model cannot account for the weak redshifted CO absorption component seen at +100 km s\(^{-1}\), however. Judging from the relative strengths of the low and high J absorptions at this velocity (see Fig. 4), the redshifted CO appears is warmer than the blueshifted CO, and therefore probably is located interior to it. Thus the actual geometry of the continuum source and the absorbing gas may be quite complex.

### 3.3. Star Formation or AGN

It has been argued by Evans et al. (2002) that star formation is rampant in the central regions of IRAS 08572+3915 NW, and thus we consider if the observed high velocities of the CO lines could be the result of such activity. The mid-infrared continuum of IRAS 08572+3915 NW arises in a region less than 250 pc in diameter (Soifer et al. 2002) and thus the putative young stars would be confined to that region, which is roughly the size of the CO millimeter line emission (Evans et al. 2002). In star-forming regions winds from young stellar objects (YSOs) shock-heat and sweep up cloud material. Veilleux, Sanders, & Kim (1999) have detected emission lines in IRAS 08572+3915 NW from the first excited vibrational state of H\(_2\), which could be emitted by shock-heated gas as a result of star formation. The observed absorption by high velocity CO could arise in numerous dense and thin shells of swept-up post-shock gas in a large number of discrete star-forming clouds seen against the continua from the a widely distributed set of YSOs. A large preponderance of blueshifted absorption over redshifted absorption would be expected, as is observed.

Despite the above considerations this explanation of the observed continuum and high velocity absorption lines as being the result of myriads of individual star-forming events over a very extended region seems contrived. Moreover, the mean velocity of the warm blueshifted CO is considerably higher than would be expected based on observations of outflows from YSOs in the Galaxy. A further difficulty with it is that, even in the most active star-forming regions in the Galaxy, such as OMC-1, the bulk of the molecular gas is at temperatures much less than 200 K. Only a small portion of the gas, located just downstream from the
shocks, is so warm. However, in IRAS 08572+3915 NW the bulk of the gas producing the absorption lines is at this warm temperature.

Thus we suspect that events associated with star formation are unlikely to be responsible for the CO line profiles. Adaptive optics imaging on a large telescope of the infrared K-band continuum might provide important information on its spatial distribution and a way of discriminating between domination of the energetics by an extended starburst or a more compact source of radiation.

Imanishi, Dudley, & Maloney (2001) have claimed that a buried AGN must be the dominant luminosity source of IRAS 08572+3915 NW (and some other ULIRGS). In that case one would expect the infrared continuum source to be compact. The preponderance of blueshifted warm gas in front of the nucleus of IRAS 08572+3915 NW naturally suggests ejection of material from the AGN. The luminosity of the central source is \(2 \times 10^{12} \, L_\odot\) (Dudley & Wynn-Williams 1997); hence the \(\sim200\) K CO must be \(\sim10\) pc from the AGN. This size and the observed expansion speed imply that the ejection began \(\sim30,000\) years ago. If the cloud forms a complete shell around the AGN, the mass of the ejected material exceeds 2000 M_\odot, and the kinetic energy exceeds \(3 \times 10^{50}\) ergs, roughly comparable to the total energy liberated in a supernova.

In the unified model of AGN, the differences between Type 1 and Type 2 objects is explained by invoking a rotating toroidal cloud of dust and gas that obscurges gas in the broad line region from some viewing angles while leaving it exposed from others. The presence of both blueshifted and redshifted CO absorptions in IRAS 08572+3915 NW suggests the possibility of rotation of the absorbing gas about the central luminosity source. As in the case of expansion, the absorbing CO would need to be situated on the outside surface of the dust in order for red and blueshifted components to be seen in absorption against it. The major problem with this model is the extreme weakness of the redshifted absorption relative to the blueshifted absorption. It implies a highly asymmetric distribution of rotating material, a highly asymmetric distribution of continuum emission, or variation of the foreground extinction by several tens of visual magnitudes across the source of the infrared continuum. The possibility that the redshifted gas is at a higher temperature than the blueshifted gas is a second potential difficulty.

Thus one cannot easily interpret our observations as arising in a torus-like gaseous structure. We tentatively interpret them as probing a transient event (occurring much more rapidly than the galaxy-galaxy interaction) in the nucleus of IRAS 08572+3915 NW. Neither the consequences of a starburst or "steady-state" phenomena related to an obscured AGN (e.g., a stable torus) can provides an explanation for the CO observations. Although the transient event appears to be mainly one of ejection of material from the nucleus, the
simultaneous observation of a small amount of material approaching the nucleus suggests both a complex geometry and complex gas motions.

4. Conclusion

The broad absorption lines of CO toward IRAS 08572+3915 NW constitute the most remarkable finding of this paper. The highly velocity-shifted and warm CO implies a transient event in the nucleus, more likely to be associated with AGN activity than with massive star formation. No observations of IRAS 08572+3915 NW directly related to this phenomenon appear in previously published papers. Warm CO is not unique to this ULIRG, however. Spoon et al. (2004) have found broad absorption due to the fundamental band of CO in IRAS F10183-7111 and have recently reported several similar detections in other deeply obscured galactic nuclei (Spoon et al. 2006b). All of their observations were made at much lower spectral resolution, and hence do not resolve individual lines and determine velocities. Thus it is unclear if the apparently energetic events taking place in IRAS 08572+3915 NW are also occurring in the other galaxies. In some cases, e.g. IRAS F10183-7111, the CO that Spoon et al. have found is considerably warmer and has a larger column density than IRAS 08572+3915 NW, but their general conclusions about the shortness of the absorbing column and proximity to the central luminosity source are similar to ours.

The absorption lines of H$_3^+$ toward IRAS 08572+3915 probably arise largely in diffuse gas, as do those seen toward the Galactic center. In combination with the low velocity low J lines of CO, the H$_3^+$ could in principle provide much more detailed information on the nature of the interstellar medium of IRAS 08572+3915 NW. However, considerably higher resolution and higher sensitivity measurements than those reported here are required. Sensitive measurements of the R(2,2)$^l$ and metastable R(3,3)$^l$ line could much more tightly constrain the density and temperature of the H$_3^+$-containing clouds, as they have done for the H$_3^+$ seen along the line of sight to the Galactic center (Oka et al. 2005).

The detection of extragalactic H$_3^+$ and the high resolution infrared spectra of extragalactic CO reported here and by Spoon et al. (2003), which have resolved the fundamental band into individual lines, are the first measurements of their types. In the future, using ground-based 8–10 m class and larger telescopes along with the James Webb Space Telescope, one can anticipate that infrared spectroscopy of interstellar CO and H$_3^+$, in combination with measurements of other molecules and dust, will be a standard technique for probing the diffuse and dense clouds and gauging the nuclear activity of many distant galaxies.

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REFERENCES

Arribas, S., Colina, L., & Borne, K. D. 2000, ApJ, 545, 228

Dannerbauer, H., Rigopolou, D., Lutz, D., Genzel, R., Sturm, E., & Moorwood, A. F. M. 2005, A&A, 441, 999

Dudley, C. C. & Wynn-Williams, C. G. 1997, ApJ, 488, 720

Evans, A. S., Mazzarella, J. M., Surace, J. A., & Sanders, D. B. 2002, ApJ, 580, 749

Geballe, T. R. & Oka, T. 1996, Nature, 384, 334

Geballe, T. R., McCall, Hinkle, K. H., & Oka, T. 1999, ApJ, 510, 251

Geballe, T. R. 2000, Phil. Trans. Roy. Soc. A, 358, 2503

Geballe, T. R. 2001, in "Gaseous Matter in Galaxies and Intergalactic Space," 17th IAP Colloquium, eds. R. Ferlet, J.-M. Desert, B. Raban (Paris: Frontier Group), 231

Goldader, J. D., Joseph, R. D., Doyon, R., & Sanders, D. B. 1995, ApJ, 444, 97

Herbst, E. & Klemperer, W. 1973, ApJ, 185, 505

Imanishi, M. & Dudley, C. C. 2000, ApJ, 545, 701

Imanishi, M, Dudley, C. C., & Maloney, P. R. 2001, ApJ, 558, L93

Kobayashi, N. et al. 2000, Proc. SPIE, 4008, 1056

Lee, H.-H., Bettens, R. P. A., & Herbst, E. 1996, A&AS, 119, 111

Mason, R. E., Wright, G., Pendleton, Y., & Adamson, A. 2004, ApJ, 613, 770

McCall, B. J., Geballe, T. R., Hinkle, K. H., & Oka, T. 1998, Science, 279, 1910.

McCall, B. J., Geballe, T. R., Hinkle, K. H., & Oka, T. 1999, ApJ, 522, 338

McCall, B. J., et al. 2003, Nature, 422, 500

McKee, C. F., Storey, J. W. V., Watson, D. M., & Green, S. 1982, ApJ, 259, 647

Mountain, C. M., Robertson, D., Lee, T. J., & Wade, R. 1990, Proc. SPIE, 1235, 25

Murphy, T. W., Soifer, B. T., Matthews, K., Armus, L., & Kiger, J. R. 2001, AJ, 121, 97

Oka, T. & Epp, E. 2004, ApJ, 613, 349
Oka, T., Geballe, T. R., Goto, M., Usuda, T., & McCall, B. J. 2005, ApJ, 632, 882
Rieke, G. H. & Lebofsky, M. J. 1985, ApJ, 288, 618
Roche, P.F. & Aitken, D. K., 1984, MNRAS, 208, 841
Sanders, D. B., Scoville, N. Z., Zensus, A., Soifer, B. T., Wilson, T. L., Zylka, R., & Steppe, H. 1989, A&A, 213, L5
Sanders, D. B. & Mirabel, I. F. 1996, ARA&A, 34, 725
Shirahata, M., Nakagawa, T., Goto, M., Usuda, T., Suto, H., & Geballe, T. R. 2006, in preparation
Soifer, B. T., Neugebauer, G., Matthews, K., Egami, E., & Weinberger, A. J. 2002, AJ, 124, 2980
Spoon, H. W. W., Moorwood, A. F. M., Pontoppidan, K. M., Cami, J., Kregel, M. Lutz, D. Tielens, A. G. G. M. 2003, A&A, 402, 499
Spoon, H. W. W., et al. 2004, ApJS, 154, 184
Spoon, H. W. W., et al. 2006a, ApJ, in press (astro-ph 0509859)
Spoon, H. W. W., et al. 2006b, in "Astrochemistry: Proceedings of IAU Symposium 231," eds. D. C. Lis, G. A. Blake, & E. Herbst, in press
Thompson, R. I. 1973, ApJ, 183, 1039
Tokunaga, A. T., et al. 1998, Proc. SPIE, 3354, 512
Veilleux, S., Kim, D.-C., & Sanders, D. B., 2002, ApJS, 143, 315
Veilleux, S., Sanders, D. B., & Kim, D.-C. 1999, ApJ, 522, 139
Watson, W. D. 1973, ApJ, 183, L17
Whittet, D. C. B., et al. 1997, ApJ, 490, 729
Wright, G. S., Bridger, A., Geballe, T. R., & Pendleton, Y. 1996, in New Extragalactic Perspectives in the New South Africa, ed. D. L. Block & J. M. Greenberg (Dordrecht:Kluwer), 143

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Fig. 1.— The 3.4-4.0 μm spectrum of IRAS 08572+3915 NW at R~1500 showing the redshifted 3.4 μm interstellar hydrocarbon band and the locations of the lines of H₃⁺ detected at higher resolution. The noise can be estimated by the fluctuations in ~0.05 μm wide intervals.
Fig. 2.— Individual and mean spectra from UKIRT and Subaru of IRAS 08572+3915 NW near the locations of three lines of $\text{H}_3^+$. The high resolution spectrum of the $\text{R}(1,1)^f$ line in the Galactic center source GCS3-2 (Oka et al. 2005), binned to the same point-to-point spacing as the spectra of IRAS 08572+3915 NW, is shown at lower right and also was used to make a model spectrum of the 3.88 $\mu$m doublet at lower left.
Fig. 3.— Spectrum of IRAS 08572+3915 NW at R=7500 covering a portion of the fundamental band of CO. The atmospheric transmission is shown as a dashed line. CO v=1-0 band line positions are indicated at the bottom, for a redshift of 0.05821.
Fig. 4.— Velocity profiles of CO lines from low and high J levels. Circles are the mean of the 1-0 R(1), R(2), and P(1) lines; triangles indicate the mean of the P(6), P(8) and P(11) lines. A representative error bar (±1σ is shown.)
Table 1. Observing Log

| UT Date   | Telescope | Wavelength (µm) | R   | Exposure (min) | Weather | Calib. star       |
|-----------|-----------|----------------|-----|----------------|---------|-------------------|
| 19981227  | UKIRT     | 3.39-4.00      | 1500| 78             | clear   | HR 3690 (A3V)    |
| 20001208  | UKIRT     | 3.82-3.99      | 6000| 130            | clear   | HR 2818 (A1V)    |
| 20010109  | UKIRT     | 4.89-5.06      | 7500| 90             | clear   | HR 3579 (F5V)    |
| 20020224  | Subaru    | 3.85-3.96      | 10000| 67            | clear   | HD 90470 (A2V)   |
| 20040209  | Subaru    | 3.85-3.96      | 5000| 80             | clouds  | HR 2891 (A1V)    |
| 20040402  | Subaru    | 3.85-3.96      | 10000| 92            | clear   | HR 2891 (A1V)    |

*Calibration star observed on different date due to rapid change in weather*
Table 2. $\text{H}_3^+$ Line Equivalent Widths

| Feature     | Wavelength ($\mu$m) | $W_\lambda$              |
|-------------|---------------------|---------------------------|
| R(1,1)$^u + R(1,0)$ | 3.8813              | $1.44 \pm 0.14 \times 10^{-4}$ |
| R(1,1)$^l$     | 3.9322              | $0.39 \pm 0.12 \times 10^{-4}$ |