DISCOVERY OF SUPERThermal HYDROXYL (OH) IN THE HH 211 OUTFLOW

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ABSTRACT

We present a 5–37 μm infrared spectrum obtained with the Spitzer Space Telescope toward the southeastern lobe of the young protostellar outflow HH 211. The spectrum shows an extraordinary sequence of OH emission lines arising in highly excited rotational levels up to an energy $E_{\text{rot}} \approx 28,200$ K above the ground level. This is, to our knowledge, by far the highest rotational excitation of OH observed in the interstellar medium. The spectrum also contains several pure rotational transitions of $^{16}$H$_2$O ($v = 0$), $^{18}$H$_2$O ($v = 0$) S(0)–S(7), HD ($v = 0$) R(3)–R(6), and atomic fine-structure lines of [Fe II], [Si II], [Ne II], [S I], and [Cl II]. The origin of the highly excited OH emission is most likely the photodissociation of H$_2$O by the UV radiation generated in the terminal outflow shock of HH 211.

Subject headings: ISM: Herbig-Haro objects — ISM: individual (HH 211) — ISM: jets and outflows — ISM: molecules — shock waves

1. INTRODUCTION

OH and H$_2$O are molecules of central importance to the interstellar oxygen chemistry in many diverse environments ranging from interstellar clouds to protoplanetary disks and comets, and they act as important shock coolants due to their rich infrared spectra (e.g., Hollenbach & McKee 1979; Draine et al. 1983; Neufeld & Dalgarno 1989; Hollenbach & McKee 1989; Wardle 1999). The potential pathways leading to the formation and destruction of these molecules are now believed to be well established. However, the relative importance of these pathways in a given astrophysical environment is generally poorly constrained due to a lack of suitable observations and the complex interaction of formation, destruction, and excitation mechanisms for H$_2$O and OH.

Both molecules are expected to be formed in abundance in hot molecular gas ($T \approx 1000$ K) owing to a series of neutral-neutral reactions whose activation barriers are overcome at high temperatures. ISO (Infrared Space Observatory), SWAS (Submillimeter Wave Astronomy Satellite), and Odin observations have enhanced OH and H$_2$O abundances in stellar outflows (e.g., Giannini et al. 2001; Benedettini et al. 2002; Lerate et al. 2006; Persson et al. 2007; and Franklin et al. 2008). However, the large beam sizes prevented a detailed spatial analysis, which is essential to investigate the OH and H$_2$O formation processes that lead to the increased abundances. In addition, the submillimeter observations of H$_2$O are mostly confined to the $^{16}$OH–$^{16}$OH transition of ortho-H$_2$O at 356.9 GHz ($E_{\text{rot}} = 61$ K), and the wavelength coverage of the ISO Long Wavelength Spectrometer (LWS) limited observations of OH to rotational states with $E_{\text{rot}} \leq 1200$ K.

In this Letter, we present the first interstellar detection of rotationally excited OH at previously unobserved high excitation levels up to $E_{\text{rot}} \approx 28,200$ K in HH 211 with the Spitzer Space Telescope (Werner et al. 2004). HH 211, one of the youngest known stellar outflows, is highly collimated, of extremely high velocity (EHV; jet speed of 100–300 km s$^{-1}$) assuming an inclination of $5^\circ$–$10^\circ$ with respect to the plane of the sky; see O’Connell et al. 2005 and Lee et al. 2007, bipolar, and associated with a Class 0 protostar in the young stellar cluster IC 348. It has been studied in detail via excited H$_2$, CO, and SiO (e.g., McCaughrean et al. 1994; Gueth & Guilloteau 1999; Eisloffel et al. 2003; O’Connell et al. 2005; Caratti o Garatti et al. 2006; Tafalla et al. 2006; Lee et al. 2007). The unique combination of sensitivity, wavelength coverage, and mapping capabilities with Spitzer enables us to study the spatial structure of the HH 211 outflow bow shock and to investigate the regions of shock-induced OH and H$_2$O formation.

2. OBSERVATIONS AND DATA REDUCTION

HH 211 was observed with the Spitzer Infrared Spectrograph (IRS; Houck et al. 2004) on 2007 March 12. We mapped the outermost region of the southeastern outflow lobe using the IRS short-low (SL2/SL1, 5.2–8.7/7.4–14.5 μm), short-high (SH, 9.9–19.6 μm), and long-high (LH, 18.7–37.2 μm) modules. The nominal spectral resolution is $R = 64$–128 as a function of wavelength for the low-resolution and $R = 600$ for the high-resolution settings. The total exposure times were 588 s for each SL, 720 s for the SH, and 600 s for the LH module. We also obtained IRAC (Infrared Array Camera; Fazio et al. 2004) and MIPS (Multiband Imaging Photometer for Spitzer; Rieke et al. 2004) image mosaics of HH 211 from the Spitzer data archive (see Fig. 1).

We performed the IRS data reduction consisting of background subtraction, masking of bad pixels, extracting the spectra, and generating the spectral line maps with CUBISM version 1.50 (Smith et al. 2007). We applied CUBISM’s slit-loss correction function and expect the absolute flux calibration of our spectrum to be accurate within 20%. A calibration to the observed MIPS 24 μm photometry is unreliable due to the strong line emission and the more than 2 yr time difference between our IRS and the archival MIPS observations.

3. RESULTS

The spectrum of HH 211 displayed in Figure 2 reveals a sequence of highly excited OH ($v = 0$, $J' \rightarrow J' - 1$) pure rotational transitions arising in the $^2\Pi_{1/2}$ and $^2\Pi_{3/2}$ rotational ladders from $J' = 15/2$ to 69/2, which result in closely spaced doublets that become partly resolvable only at wavelengths greater than 20 μm in our spectra. An additional splitting due to $\Lambda$-doubling is only barely noticeable for the OH lines at the

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Fig. 1.—HH 211: Spitzer IRAC 3–9 μm + MIPS 24 μm color composite image (blue, 3.6+4.5 μm; green, 8.0 μm; and red, 24 μm). White boxes outline the IRS SL, SH, and LH map coverage including the SH/LH background position. The image center coordinates are R.A. = 3h43m56.8s, decl. = 32°00′34.4′′ (J2000).

longest wavelengths in our spectra (see Herzberg 1971 for a detailed treatment of OH spectroscopy). The OH energy level diagram in Figure 3 shows that the highest excited OH transition has an upper state energy of $E/hc = 19,607 \text{ cm}^{-1}$ ($E/k \approx 28,200 \text{ K}$) above the ground level. Note that the population of the OH energy levels probably extends to even higher energies, but the corresponding rotational transitions fall in the wavelength range of the low-resolution IRS modules below 10 μm. Due to the lower resolution, the SL modules are not sensitive enough to detect the faint, narrow emission lines.

In addition, there are OH cross-ladder transitions with $\Delta J = 0, \pm 1$, but all such transitions that fall in the 5–37 μm region have transition probabilities orders of magnitude smaller than the intraladder transitions described above. Nevertheless, we detect the two lowest excited OH ($v = 0, ^2\Pi_{1/2} \to ^2\Pi_{3/2}, J' \to J' - 1$) cross-ladder transitions with upper levels $J' = 7/2$ and $5/2$ ($E/k \approx 620$ and 420 K) at 28.94 and 34.62 μm (see Fig. 2), respectively, indicating a substantial population in the lower OH $J$-levels. We did not unambiguously detect any pure rotational OH transitions from excited vibrational levels.

The low-resolution portion of the spectrum is dominated by the strong, pure rotational H$_2$ (0–0) $S(0)$–$S(7)$ transitions and the much weaker [Fe II] 5.34 μm line. In addition to the previously mentioned OH lines, the high-resolution portion longward of 10 μm shows H$_2$ (0–0) $S(0)$–$S(2)$ including (1–1) $S(3)$ at 10.18 μm, HD (0–0) $R(3)$–$R(6)$, numerous H$_2$O ($v = 0$) pure

Fig. 2.—Background-subtracted Spitzer IRS spectrum of HH 211: all major detected lines are labeled, and the strongest H$_2$O lines are marked with an asterisk. The strongest lines are clipped for illustration purposes.
rotational lines, and forbidden atomic fine-structure lines from [Fe II], [Si II], [Ne II], [S I], and [Cl I]. The spectrum also has noticeable continuum emission longward of 15 μm, which can be fitted by thermal dust emission at a temperature ~85 K, represented by a modified blackbody with the dust emissivities of Weingartner & Draine (2001). Two additional components at about 170 K and 30 K are needed to fit the complete continuum including the 8–15 μm region and the MIPS 70 μm flux of $F_\nu = 1.1 \times 10^{-16}$ W m$^{-2}$ μm$^{-1}$. There is also a strongly rising continuum shortward of 8 μm. The peculiar NIR continuum of HH 211 was previously noted by Eislöffel et al. (2003) and confirmed by O’Connell et al. (2005), who interpret it as scattered light from the protostar escaping along the low-density jet cavity.

4. DISCUSSION

4.1. The Origin of High-J OH Emission

In § 3, we reported the detection of rotationally excited OH at previously unobserved high excitation levels in HH 211. As a consequence of the large OH dipole moment, the observed intraladder pure rotational transitions have large Einstein A-coefficients of the order of 10–400 s$^{-1}$. For comparison, our observed pure rotational H$_2$O transitions have $A \sim 1–20$ s$^{-1}$, the [Fe II] $S(0)$–$S(7)$ pure rotational lines have $A$-values of a few $\times 10^{-1}$ s$^{-1}$, and the H$_2$O $S(0)$–$S(1)$ pure rotational lines have $A$-values between $3 \times 10^{-3}$ and $3 \times 10^{-11}$ s$^{-1}$. Large $A$-values make collisional excitation of high energy levels very ineffective at lower densities; i.e., the corresponding critical densities are usually much larger than the gas density. The observed OH lines in HH 211 demonstrate that energy levels up to at least $E/k \approx 28,200$ K are well populated despite the large OH $A$-values. This fact, coupled with the observed distribution of OH line intensities, strongly suggests a selective, nonthermal origin of the high-J OH excitation. For comparison, a non-LTE analysis of the [Fe II] $S(0)$–$S(7)$ lines in our spectrum suggests a gas temperature less than a few 1000 K. Furthermore, all of our observed pure rotational H$_2$O lines originate from energy levels with $E/k \approx 2400$ K even though there are many pure rotational H$_2$O transitions with $A \sim 50–100$ s$^{-1}$ from energy levels between 3000 and 8000 K in the 10–38 μm wavelength range.

Theoretical and experimental laboratory studies show that OH molecules produced via photodissociation of H$_2$O at photon energies larger than about 9 eV ($\lambda < 140$ nm) are mostly in the ground electronic and vibrational state but with a high rotational excitation favoring $J = 70/2–90/2$ with $E/k \gtrsim 30,000$ K (Mordant et al. 1994; van Harrevelt & van Hemert 2000; Harich et al. 2000). This is because the absorption of UV radiation in the H$_2$O ($B$–$X$) band produces OH in an excited electronic state, $A ^2Σ^+$, which, in turn, efficiently yields highly excited ground-state OH ($X^2Π$) molecules via a nonadiabatic crossing between intersecting potential energy surfaces (see van Harrevelt & van Hemert 2000; Harich et al. 2000). This process leads to a highly selective formation of high-J OH in the ground electronic and vibrational state, followed by a radiative cascade down the rotational ladders depicted in Figure 3. This is consistent with our observed distribution of OH line intensities and our nondetection of OH pure rotational transitions from excited vibrational states. We will present a detailed non-LTE excitation model of OH, H$_2$O, and H$_2$ together with an analysis of the atomic fine-structure transitions in a subsequent paper.

Further evidence for the role of H$_2$O photodissociation as a source of high-J OH can be gained from spatial mapping of the emission lines. Our Spitzer IRS maps cover the southeastern terminal shock of HH 211, which exhibits a typical bow shock geometry in H$_2$ and CO emission (Gueuht & Guilloteau 1999; Eislöffel et al. 2003). Figure 4 shows the spatial distribution of rotationally excited OH and H$_2$O together with the 25 μm dust continuum surface brightness. The highly localized optical Ha emission (Walawender et al. 2006) is practically coincident with the 25 μm surface brightness maximum. Their emission maxima are offset by about 1″, which is within the positional map accuracy. This region is located at the bow shock apex, where the shock velocity is expected to be the highest and presumably most of the shock-generated FUV radiation originates. The emission maximum of rotationally excited OH (Fig. 4, left map) also coincides with the bow shock apex. Although not shown in Figure 4 due to the limited spatial coverage, the emission maximum of the OH ($J' > 29/2$) rotational lines in the SH wavelength range occurs at the same location. However, unlike Ha, the continuum, OH, and H$_2$O emissions clearly extend well beyond the bow shock. Using the 25 μm continuum surface brightness as a surrogate tracer of the UV radiation field, we clearly note the presence of a radiative precursor upstream of the shock. Note that although collisional grain heating due to inelastic gas-grain collisions may contribute to the dust heating in the bow shock, it is probably unimportant outside and ahead of the shock.
4.1.1. Formation of OH and H$_2$O

Our emission-line maps show clear evidence of OH and H$_2$O emission in the precursor region (see Fig. 4). It is unlikely that the chemical formation route via H$_2$ + O → OH + H and H$_2$ + OH → H$_2$O + H (e.g., Hollenbach & McKee 1979; Neufeld & Dalgarno 1989) is the dominant source of OH and H$_2$O in the UV precursor upstream of the shock. These reactions have significant Arrhenius activation energies ($E_a/k$ about 3150 and 1736 K, respectively) and proceed efficiently only in dense, hot gas. The absence of rovibrational H$_2$ emission in the precursor region confirms the absence of hot, shocked gas needed to directly form OH and H$_2$O through gas chemistry.

Instead, we propose that UV-induced photodesorption of water ice from grain mantles and photodissociation of H$_2$O either in the gas phase or directly in the grain ice mantles (see Andersson et al. 2006) are the primary sources of OH and H$_2$O in the precursor. We evaluated the H$_2$O photodesorption rate using the Lyα-dominated FUV emission generated by a shock with a speed of $v_s = 40$ km s$^{-1}$ and a preshock density of $n_0 = 10^2$–$10^4$ cm$^{-3}$ (atomic shock models by J. Raymond 2008, private communication). Such a shock approximately reproduces our observed [Ne ii] 12.8, [S i] 25.2, [Fe ii] 26.0, and [Si ii] 34.8 μm emission-line intensities, which are good indicators for $v_s$ and $n_0$ (see, e.g., Fig. 7 in Hollenbach & McKee 1989). Our estimate shows that grain ice mantles can be efficiently removed via photodesorption on timescales of the order of 10$^3$ yr assuming the experimentally measured Lyα photodesorption yield for water ice of ($3$–$5$) × 10$^{-7}$ molecules per photon and a Lyα photodesorption cross section ~8 × 10$^{-18}$ cm$^2$ per individual water ice molecule (Westley et al. 1995a, 1995b). This is consistent with the estimate of Hollenbach & McKee (1979), who argued that a shock with $v_s = 40$ km s$^{-1}$ would lead to complete upstream photodesorption of grain ice mantles assuming a photodesorption yield of 5 × 10$^{-7}$. At the high visual extinction toward the terminal shock of the HH 211 southeastern lobe, $A_V ≈ 12 ± 3$ mag (O’Connell et al. 2005; Caratti o Garatti et al. 2006), most of the gas-phase water would otherwise be expected to reside frozen onto grains (cf. Melnick & Bergin 2005).

It is interesting to compare our observation of HH 211 with a recent Spitzer IRS detection of strong water emission toward the protostellar object IRAS 4B in NGC 1333 by Watson et al. (2007). These authors attribute the origin of this emission to the very dense, warm molecular layer of a protoplanetary disk. In this case, the main source of water is probably thermal sublimation of grain ice mantles in the ~170 K warm surface layer as suggested by Watson et al. (2007). Sublimation is insignificant at grain temperatures below about 100 K (cf. the derived dust temperature of ~85 K in HH 211 from our dust continuum fit, see § 3), but it becomes rapid above 120 K (see Fraser et al. 2001, Table 2). In addition to the strong H$_2$O emission, we have subsequently identified OH emission limited to transitions with $J' < 21/2$ ($E_{J'} ≲ 3500$ K) in the IRS LH spectrum of IRAS 4B by reanalyzing the Spitzer archival spectra originally published by Watson et al. (2007). The comparatively low excitation of OH indicated by the absence of lines with $J' = 23/2$ to 27/2 and the weakness of the OH emission relative to H$_2$O in IRAS 4B are consistent with the proposed sublimation origin of water and suggest that FUV photodissociation of H$_2$O plays only a minor role compared to HH 211.

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