[Fe II] 1.64 μm IMAGING OBSERVATIONS OF THE OUTFLOW FEATURES AROUND ULTRACOMPACT H II REGIONS IN THE FIRST GALACTIC QUADRANT

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Received 2014 May 12; accepted 2014 August 4; published 2014 September 3

ABSTRACT

We present [Fe II] 1.644 μm features around ultracompact H II regions (UCHIIs) found on a quest for the “footprint” outflow features of massive young stellar objects (MYSOs). We surveyed 237 UCHIIs in the first Galactic quadrant, employing the CORNISH UCHII catalog and UWIFE data, which is an imaging survey in the [Fe II] 1.644 μm performed with UKIRT-WFCAM under ~0′′8 seeing conditions. The [Fe II] features were found around five UCHIIs, one of which was less plausible. We interpret the [Fe II] features to be shock-excited by outflows from YSOs and estimate the outflow mass-loss rates from the [Fe II] flux which are ∼1 × 10⁻⁶–4 × 10⁻³ M⊙ yr⁻¹. We propose that the [Fe II] features might be the “footprint” outflow features, but more studies are required to clarify whether or not this is the case. This is based on the morphological relation between the [Fe II] and 5 GHz radio features, the outflow mass-loss rate, the travel time of the [Fe II] features, and the existence of several YSO candidates near the UCHIIs. The UCHIIs accompanying the [Fe II] features have relatively higher peak flux densities. The fraction of UCHIIs accompanied by the [Fe II] features, 5/237, is small when compared to the ~90% detection rate of high-velocity CO gas around UCHIIs. We discuss some possible explanations for the low detection rate.

Key words: H II regions – infrared: ISM – ISM: jets and outflows – shock waves – stars: formation – surveys

Online-only material: color figures

1. INTRODUCTION

The formation of massive stars (M > 8 M⊙) is still unclear in many aspects (Zinnecker & Yorke 2007). One question to be resolved is how massive stars obtain their mass. It has been reported more often that, as in low-mass stars, the disk-mediated accretion process seems to be involved in forming massive stars (e.g., Beuther et al. 2002; Wu et al. 2004; San José-García et al. 2013; Cooper et al. 2013). However, it is still uncertain if disk accretion works in the mass range of M > 25 M⊙ (Zinnecker & Yorke 2007).

One way to grasp the accretion process of massive young stellar objects (MYSOs) is by tracing the outflow features. In order for the massive (proto)star to accrete mass, the angular momentum of the infalling material must be removed. If it were not, then the angular momentum of the infalling material would keep piling on the massive (proto)star, and the (proto)star would rotate with ever-increasing velocity. The outflow plays a significant role in removing this angular momentum (Lada 1985; Bachiller 1996) and produces outflow features in and around the MYSO. Therefore, by tracing these outflow features we can study the MYSO accretion history. In principle, we can study “early stage” accretion activity even when the MYSO has already evolved to the “late-stage” using the outflow features.

Ultracompact H II regions (UCHIIs; size ≲ 0.1 pc, density > 10⁴ cm⁻³) are thought to be the late stage of MYSOs and are no longer accreting significant mass (Churchwell 2002; Zinnecker & Yorke 2007). Since UCHII’s natal clumps are not yet completely destroyed, we may expect that the materials ejected during the past, active accretion phase are still producing shocked features around the UCHIIs, colliding with the natal clump. In addition, shocked features can also be produced from the internal working surfaces of jets and outflows (Reipurth & Bally 2001; Arce et al. 2007). We will call these shocked features “footprint” outflow features, emphasizing the time difference between the current MYSO stage (i.e., UCHII) and the past MYSO stage when the outflowing material was launched. We thus expect high outflow mass-loss rates from the “footprint” outflow features, since the outflowing material was launched during the earlier active accretion phase.

These “footprint” outflow features are observable through radiative cooling lines, such as [Fe II] 1.64 μm, H₂ 2.12 μm, and CO radio lines (Hollenbach & McKee 1989; Neufeld & Dalgarno 1989; Kaufman & Neufeld 1996; Wilgenbus et al. 2000; Flower & Pineau Des Forêts 2010). Indeed, CO outflow features have been observed around UCHII regions, such as G5.89-0.39 (Watson et al. 2007; Wood & Churchwell 1989), G18.67+0.03 (Cyganowski et al. 2012), G25.65+1.05 (Shepherd & Churchwell 1996), and G240.31+0.07 (Shepherd & Churchwell 1996). The dynamical timescale of these CO outflow features is > 10⁴ yr, which is comparable to the typical lifetime of UCHII (~4 × 10⁴ yr; Wood & Churchwell 1989; González-Avilés et al. 2005) and MYSO jet-phase (~10³–4 × 10⁴ yr; Mottram et al. 2011; Guzmán et al. 2012).

However, the CO outflow observations toward UCHIIIs have been performed with low spatial resolutions greater than several arc seconds, limiting detailed study of the accretion history, e.g., outflow morphology. Hence, [Fe II] line observations on the ground, the typical seeing of which is ∼1′′0, can be useful, although their ability to trace outflows is limited by the depletion of Fe, and the requirements of high density and high shock velocity. The H₂ 2.12 μm emission line is not useful for tracing outflow features around UCHIIIs, which emit intense...
UV, because the emission line is easily excited by far-UV radiation (Hollenbach & Tielens 1997). Here, we present the [Fe II] 1.64 μm features around UCHIIs observed at a spatial resolution of FWHM ∼0.8. We employed the UKIRT imaging survey of the first Galactic quadrant in [Fe II] 1.64 μm, i.e., the UWIFE survey (Lee et al. 2014), with the UCHII catalog from the CORNISH survey (Hoare et al. 2012; Purcell et al. 2013). Of 237 UCHIIs, 5 UCHIIs were found to have nearby [Fe II] features, 1 of which was less plausible. We estimate the outflow mass-loss rate from [Fe II] features can be the “footprint” outflow features. The relations between the [Fe II] detection rate and the UCHII parameters from the CORNISH catalog are also discussed.

2. OBSERVATIONS AND DATA REDUCTION

We used the [Fe II] imaging data from the UWIFE survey (Lee et al. 2014). This survey covers the first Galactic quadrant (7° < l < 63°, |b| < 1°) using the [Fe II] 1.64 μm narrow-band filter. The [Fe II] filter was installed in the Wide-Field Camera (WFCAM, Casali et al. 2007) of the United Kingdom Infrared Telescope (UKIRT). The WFCAM provides four HgCdTe Rockwell Hawaii-II arrays (2048 × 2048), each of which has a field of view of 13.7′ × 13.7′. These four arrays are located off-center, forming a square with a 12.9 gap. With this layout, observing at four discrete positions results in a contiguous area covering 0.75 deg² on the sky, i.e., a WFCAM tile.

The UWIFE surveys were performed through 2012 and 2013, and the observed tiles are shown as gray shaded tiles in Figure 1. The two UCHIIs (G061.7207+00.8630 and G065.2462+00.3505) uncovered with the UWIFE survey were separately observed by targeting.

In order to find [Fe II] features, we used continuum-subtracted [Fe II] images and RGB composite images of [Fe II] and H (see Figures 2 and 3). The H-band images are from the UKIRT Infrared Deep Sky Survey (UKIDSS) Galactic Plane Survey (GPS; Lucas et al. 2008; Lawrence et al. 2007), and the continuum subtraction was performed as described in Lee et al. (2014). We note that there is a time gap of a few years between the [Fe II] and H images. Therefore, time-variable continuum features can mimic [Fe II] features in the continuum-subtracted and RGB composite images mentioned above. This is more important considering that some UCHIIs show morphological changes on timescales of years (Acord et al. 1998; Franco-Hernández & Rodríguez 2004; van der Tak et al. 2005; Galván-Madrid et al. 2008), which suggests changes of the UCHII radiation environment.

We searched a ∼2.4 × 2.4 area around the UCHII sources and found five UCHIIs that had [Fe II] features nearby. We only selected the [Fe II] features not in contact with the 5 GHz radio features (see Figure 2) in order to exclude [Fe II] features produced by the expanding H II regions. We also excluded pointlike [Fe II] features, since we cannot tell if they are variable stars or pointlike outflow features due to the time gap between the [Fe II] and H images mentioned above. These two types of excluded features are shown in Figure 4 as examples. Among the selected targets, we filtered out the UCHIIs whose [Fe II] features were less plausible and named them “candidates.” One of five selected UCHIIs is classified as a candidate. Figure 2 shows the UCHIIIs accompanying [Fe II] features while Figure 3 shows the candidate. The CORNISH 5 GHz image with a super resolution of ∼1″5 (Purcell et al. 2013) is also shown for reference. More specific descriptions for individual objects are given below.

3. ANALYSIS AND RESULTS

3.1. [Fe II] Feature Detection around UCHIIs

We searched for [Fe II] features around UCHIIs using the candidate UCHII catalog of the CORNISH survey (Hoare et al. 2012; Purcell et al. 2013). The CORNISH survey was performed with the Very Large Array at 5 GHz over the first Galactic quadrant (10° < l < 65°, |b| < 1°), which matches well with the coverage of our UWIFE survey (Figure 1). The average beam sizes are ∼1″5 and ∼1″2 for the major and minor axes, respectively (Hoare et al. 2012). The catalog contains 240 sources and we checked all of them except for three, which had no corresponding H-band image for continuum subtraction. The three unchecked UCHIIIs are G025.3970+00.5614, G025.3983+00.5617, and G025.7157+00.0487. Figure 1 shows the distribution of the CORNISH UCHII catalog sources plotted over the UWIFE survey coverage.

Figure 2(a) shows the [Fe II] features around two UCHIIs: G025.3809−00.1815 and G025.3824−00.1812. These UCHIIs
Figure 2. Outflow features around CORNISH sources seen in the continuum-subtracted [Fe ii] (top panels) and RGB composite (middle panels; $R = H$, $G = [Fe \, ii]$, $B = H$) images. The [Fe ii] and H images (FWHM ~ 0'8) are from the UWIFE (Lee et al. 2014) and UKIDSS (Lucas et al. 2008) surveys, respectively. The CORNISH 5 GHz image (FWHM ~ 1'5) is shown for reference in the bottom-left panel. The dashed boxes in the left panels indicate the region enlarged in the right panels. Ellipses indicate where the flux is measured (on-source:solid, off-source:dashed). The ellipse pairs (on+off) are alphabetically tagged in order of increasing R.A. (cf. top-right panel). Circles with a red slash indicate the region excluded during the flux measurement. The measured fluxes are listed in Table 1.

(A color version of this figure is available in the online journal.)

are also cataloged in Thompson et al. (2006). These two UCHIIs reside within the massive star cluster W 42, whose bright central star shows an MK-type spectrum of O5–O6 (Blum et al. 2000). The [Fe ii] features locate southwest of the two UCHIIs and show several knotty structures almost in a line pointing toward the two UCHIIs (see the white dashed box of Figure 2(a)). We note here the diffuse southeast-northwest continuum features in the upper left corner of the middle left
panel of Figure 2(a), which are located in a symmetric position to the [Fe II] features with respect to the UCHIIs (see also Figure 7(a)). We can further trace the [Fe II] features closer to the two UCHIIs in the continuum-subtracted image, although its clear identification is hindered by strong diffuse continuum emissions and the crowded point sources near the two UCHIIs. The [Fe II] features show no overlap with the radio feature seen in the CORNISH 5 GHz continuum image, and hence they seem to have no direct contact. We note that the 5 GHz morphology of G025.3809−00.1815 extends toward the [Fe II] features.

3.1.2. G028.2879−00.3641

Figure 2(b) shows the [Fe II] features around the UCHII G028.2879−00.3641. This UCHII is also cataloged in Kurtz et al. (1994) and Walsh et al. (1998). The environment of G028.2879−00.3641 is not crowded as much as those of
G025.3809$-$00.1815 and G025.3824$-$00.1812. The [Fe II] features are locate to the west of the UCHII, showing an elongated shape (see white dashed box of Figure 2(b)). The elongated [Fe II] feature is stretched along the direction roughly perpendicular to the line connecting the UCHIIs and the [Fe II] features. It is hard to check whether or not any [Fe II] feature exists near the UCHII, since diffuse continuum emissions are so strong. The [Fe II] features show no overlap with the radio feature seen in the CORNISH 5 GHz continuum image, and hence they seem to have no direct contact. The 5 GHz morphology extends roughly along the direction to the [Fe II] features, as seen in G025.3809$-$00.1815.

3.1.3. G050.3152+00.6762 and G050.3157+00.6747

Figure 2(c) shows the [Fe II] features around two UCHIIs: G050.3152+00.6762 and G050.3157+00.6747. These UCHIIs are also cataloged in Wood & Churchwell (1989). The environment of the two UCHIIs is not as crowded as those of
Figure 3. Candidate outflow features around CORNISH sources G013.8726+00.2818 seen in the continuum-subtracted [Fe II] (top) and RGB composite (middle R = H, G = [Fe II], B = H) images. The candidate [Fe II] features are indicated by arrows for clarity. The [Fe II] and H images (FWHM $\sim 0.8''$) are from the UWIFE (Lee et al. 2014) and UKIDSS (Lucas et al. 2008) surveys, respectively. The CORNISH 5 GHz image (FWHM $\sim 1.5''$) is shown for reference in the bottom panel. (A color version of this figure is available in the online journal.)

Figure 4. Example of excluded [Fe II] features (arrows) around UCHII G023.9564+00.1493, seen in the continuum-subtracted [Fe II] image (top), RGB composite image (middle; R = H, G = [Fe II], B = H), and CORNISH 5 GHz image (bottom). (A color version of this figure is available in the online journal.)
G025.3809−00.1815 and G025.3824−00.1812. The [Fe II] features locate between the two UCHIIs at the northern part, and show knotty or elongated structures (see white dashed box of Figure 2(c)). The strong knotty feature seen in the continuum-subtracted image (near the upper left corner of the white dashed box) also shows a pointlike feature in the H-band image. This [Fe II] feature could be a fake caused by the temporal variation of the shape of the UCHII is well matched by the dark lane seen in the radio feature observed in the CORNISH 5 GHz continuum image. The [Fe II] extended shapes. The features located at the east, north, and northwest of the UCHII, showing direct physical contact; in this case, the [Fe II] feature is excluded from our examination because we only chose [Fe II] features not overlapping with the 5 GHz radio feature (see above). On the other hand, this elongated [Fe II] feature may be related to G050.3152+00.6762, since its stretching orientation is pointing toward G050.3152+00.6762, and G050.3157+00.6747 shows no [Fe II] feature along its edge except on the north-west edge. In that case, the elongated [Fe II] feature can be interpreted as a jetlike feature that has no direct contact with the UCHII. Unlike previous UCHIIs, the 5 GHz radio feature of G050.3152+00.6762 does not extend toward the [Fe II] features.

3.1.4. Candidate: G013.8726+00.2818

Figure 3 shows the [Fe II] features around the UCHII G013.8726+00.2818 (see the arrows). The [Fe II] features are located at the east, north, and northwest of the UCHII, showing extended shapes. The H-band image also shows similar extended features in the area of the [Fe II] features. Therefore, the [Fe II] features could be fakes caused by the temporal variation of the extended continuum emissions; we thus classify this UCHII as a candidate. The [Fe II] features show no overlap with the crescent radio feature observed in the CORNISH 5 GHz continuum image, and hence they seem to have no direct contact. The crescent shape of the UCHII is well matched by the dark lane seen in the RGB composite image, and extends roughly toward the [Fe II] features.

3.2. [Fe II] Flux Measurement and Extinction Correction

In order to characterize the physical quantity of the detected [Fe II] features, we measured their fluxes. The candidate [Fe II] features were excluded from the flux measurements because they may not be real [Fe II] features. We chose some regions for measurement which are shown in the right panels of Figure 2: on-source (solid line) and off-source (dashed line). Each region is labeled with a letter of the alphabet in order of increasing R.A., and their positions are listed in Table 1. For region name simplicity, we just selected one UCHII for the name prefix when there were two UCHIIs. The measured [Fe II] flux in each region is also listed in Table 1.

We then corrected the extinction effect on the measured [Fe II] flux employing the extinction curve of "Milky Way, $R_V = 3.0$" (Weingartner & Draine 2001; Draine 2003). The amount of extinction was estimated by obtaining the total H column density ($N_H$) from the color excess. The extinction and the corrected [Fe II] flux are listed in Table 1. The following sections describe how we obtained the extinction for the individual targets. The extinctions are $A_V \sim 9–20$, which is relatively small compared to the typical value of UCHIIs, $A_V \sim 30–50$ (Hanson et al. 2002).

3.2.1. G025.3809−00.1815 and G025.3824−00.1812

We adopted the color excess $E(H - K)$ estimated from the assumption that the massive stars of the cluster are on the main sequence (Blum et al. 2000). The observed and intrinsic colors are $(H - K) = 0.637$ and $(H - K)_0 = -0.05$ in the CIT system, respectively. We used the effective wavelengths for Vega in the CIT system (Bessell & Brett 1988) when deriving the total H column density. $A_{FeII}$ is about 1.64 mag.

3.2.2. G028.2879−00.3641

We estimated the color excess $E(H - K)$ using the UKIDSS photometry data (Lucas et al. 2008). We chose the point source that corresponds to the UCHII catalog position and assumed that the extinction toward this source and the [Fe II] features were the same. The color of the selected UKIDSS source is $(H - K) = 0.556$. We assumed that this source was on the main sequence and adopted the intrinsic color of $(H - K)_0 = -0.04$ (Koornneef 1983). These two colors were compared in the 2MASS system, using the relations in Lucas et al. (2008) and Carpenter (2001). We used the isophotal wavelengths of the 2MASS system (Cohen et al. 2003) when deriving the total H column density. $A_{FeII}$ is about 1.60 mag.

3.2.3. G050.3152+00.6762 and G050.3157+00.6747

We estimated the color excess $E(J - H)$ using the UKIDSS photometry data (Lucas et al. 2008). We chose two point sources which, respectively, correspond to the two UCHII catalog positions. The colors of the selected UKIDSS sources are $(J - H) = 1.196$ for G050.3157+00.6747 and $(J - H) = 2.054$ for G050.3152+00.6762, respectively. We used the mean value for the observed color. The color $(J - H)$ is used rather than $(H - K)$, because the UKIDSS photometry data do not provide the K-band photometry. We assumed that the two sources were on the main sequence and adopted the intrinsic color of $(J - H)_0 = -0.13$ (Koornneef 1983). These two colors were compared in the 2MASS system, using the relations in Lucas et al. (2008) and Carpenter (2001). We used the isophotal wavelengths of the 2MASS system (Cohen et al. 2003) when deriving the total H column density. $A_{FeII}$ is about 3.71 mag.

3.3. Excitation Mechanism for the [Fe II] Features

In this section, we examine the excitation mechanism for the observed [Fe II] features. We think the [Fe II] features are probably excited by shocks rather than UV radiation, as listed below. The shock driver is likely to be outflows from YSOs, because, in star forming regions, they are the most probable source generating supersonic motions that result in the observed [Fe II] features.

First, the [Fe II] features show different morphology from the diffuse near-infrared continuum features, which indicate the irradiated area. The dominant UV radiation sources in the region are the massive stars ionizing the UCHII, and it is known that the [Fe II] emission well traces the warm neutral zone in the photo-dissociation regions (Burton et al. 1990). If the [Fe II] features are radiatively excited, then they should show features similar to the continuum features. However, this is not the case (see Figures 2 and 5). Additionally, in

5 This near-infrared continuum is almost certainly dust-scattered light. It is not likely to be from thermal dust, since the temperature should be as high as $\sim 10^3$ K. This high dust temperature is not easy to achieve in the photo-dissociation region (see Hollenbach & Tielens 1997). Such a temperature is observed at supernovae (e.g., Fox et al. 2009).
the cases of G025.3809−00.1815, G025.3824−00.1812 (Figures 2(a) and 5(a)), and G028.2879−00.3641 (Figures 2(b) and 5(b)), there are continuum features that locate closer to the UCHII than the observed [Fe ii] feature. These continuum features have no corresponding [Fe ii] feature, which means the radiatively excited [Fe ii] is weak. Therefore, the observed [Fe ii] features have an even lower probability of being radiatively excited. We note that G050.3157+00.6747 (the left UCHII in Figures 2(c) and 5(c)) is excluded from this examination, because we only considered the link between G050.3152+0.06762 (the right UCHII in Figures 2(c) and 5(c)) and the [Fe ii] feature (see Section 3.1.3).

Second, the observed [Fe ii] features locate far from the ionized regions, i.e., UCHII, as can be seen from the 5 GHz radio images (Figure 2). Therefore, the intensity of the hydrogen recombination line at the location of the observed [Fe ii] features would be low. Considering that the photo-ionized gas shows a line ratio of [Fe ii]/Brγ ≃ 0.1−2.5 (Aloño-Herrero et al. 1997), the intensity of the photoionized [Fe ii] line would also be low at the location of the observed [Fe ii] features.

### 3.4. Estimation of Outflow Mass-loss Rate

Based on the argument that the [Fe ii] features are probably shock-excited by outflows from YSOs (see Section 3.3), we estimate the outflow mass-loss rate ($M_{\text{out}}$) from the [Fe ii] flux (Table 1) in two different ways (see Section 3.2 of Shinn et al. 2013). We refer to them as the “Fe-Shell” and “Fe-Stream” methods, respectively.

The “Fe-Shell” method assumes that the [Fe ii] feature is excited by the wind shock and the ambient shock, both of which are J type (for shock types, see Draine & McKee 1993), when the outflowing material is colliding with the ambient medium (see Figure 3 of Shinn et al. 2013). We estimate $M_{\text{out}}$ through the shock luminosity. The shock luminosity, which is expressed in terms of $M_{\text{out}}$, is derived from the [Fe ii] flux employing the shock model calculation. The “Fe-Stream” method assumes that the [Fe ii] feature is a well-collimated stream of ionized gas flowing from the outflow source. We derive the total mass of the collimated medium from the [Fe ii] flux, assuming the typical excitation condition of [Fe ii] line. Then, we estimate the travel time from the measured outflow length and the assumed outflow velocity. From these mass and time values, we estimate $M_{\text{out}}$.

We applied the “Fe-Shell” and “Fe-Stream” methods to the knotty and longish [Fe ii] features, respectively. The “Fe-Stream” method is only applicable to the [Fe ii] feature in Figure 2(c), relating it to the UCHII G050.3152+00.6762. The Fe depleting onto dust grains is also considered for both methods, in order to reflect Fe depletion in jets (e.g., Beck-Winchatz et al. 1996; Mouri & Taniguchi 2000; Nisini et al. 2002, 2005; Podio et al. 2006; Giannini et al. 2008, 2013; Antonucci et al. 2014). The logarithmic abundance of $\lesssim -4.63$ (Allen et al. 2008), which is depleted by 0.1 dex (Asplund et al. 2009), is used for the “Fe-Shell” method. We apply the same depleted abundance for the “Fe-Stream” method, i.e., $A_{\text{Fe/He}} = 2.3 \times 10^{-3}$ (see Equation (10) of Shinn et al. 2013). Table 2 lists the method used and the results, and $M_{\text{out}}$ ranges $\sim 1 \times 10^{-6} - 4 \times 10^{-5} M_{\odot} \text{yr}^{-1}$.

In applying the “Fe-Shell” method to G025.3809−00.1815-B and G025.3809−00.1815-C (Figure 2(a)), we modify Equation (8) of Shinn et al. (2013). These [Fe ii] features have the corresponding H2 ν = 1 → 0 S(1) 2.12 μm features (Figure 5(a)), and the [Fe ii] features probably come from the wind shock alone, rather than both the wind and ambient shocks. We think the H2 feature is likely from C-type shocks rather than J-type shocks because only some of the observed [Fe ii] features accompany the H2 features. In this sense, the ambient shock is more likely to be C type than the wind shock, since the ambient shock is propagating into a denser medium. Therefore, we modified Equation (7) of Shinn et al. (2013) to be $L_{\text{mech}} = 1/2 M_{\text{sw}} v_{\text{sw}}^2$, and hence Equation (8) of Shinn et al. (2013) is modified to $L_{\text{mech}} = 4/27 M_{\text{out}} v_{\text{out}}^2$. G028.2879−00.3641 has some filamentary H2 features around it (Figure 5(b)), but its morphology is different from that of [Fe ii] features (Figure 2(b)). We think this H2 feature is probably excited by radiation because it closely follows the near-infrared continuum features (see Section 3.3).

Table 2 also lists other physical parameters required for the $M_{\text{out}}$ estimation. We adopted the outflow velocity of 200 km s$^{-1}$ because it falls within the typical outflow velocity of YSOs (Reipurth & Bally 2001); the J shock develops for a shock velocity of $>50$ km s$^{-1}$ under the typical cloud environments (Draine & McKee 1993; Le Bourlot et al. 2002). We adopted 100 km s$^{-1}$ for G025.3809−00.1815-B and G025.3809−00.1815-C (Figures 2(a) and 5(a)) in order to make the ambient shock velocity slow enough to be C type. The length scale and solid angle of the [Fe ii] feature are from the ellipse used for the [Fe ii] flux measurement (see Section 3.2). The distance to the individual UCHII was adopted as described in the following sections. We note that the $M_{\text{out}}$ estimation includes the uncertainties that originate from several assumptions, such as Fe depletion, the

| Region | R.A., Decl. (J2000) | $A_{\text{V}}$ | Observed [Fe ii] Flux | Dereddened $^{d}$ |
|--------|---------------------|-------------|-----------------------|-----------------|
| G025.3809−00.1815-A | 18:38:12.719, −6:48:26.63 | 8.9 | 5.2 ± 0.2 | 23.9 ± 0.9 |
| G025.3809−00.1815-B | 18:38:13.373, −6:48:23.26 | 8.9 | 2.8 ± 0.2 | 12.6 ± 0.7 |
| G025.3809−00.1815-C | 18:38:13.608, −6:48:19.85 | 8.9 | 6.6 ± 0.2 | 30.0 ± 0.9 |
| G028.2879−00.3641-A | 18:44:12.210, −4:17:50.44 | 8.7 | 2.5 ± 0.1 | 10.9 ± 0.5 |
| G028.2879−00.3641-B | 18:44:14.242, −4:17:56.37 | 8.7 | 6.1 ± 0.2 | 26.6 ± 0.8 |
| G050.3152+00.6762-A | 19:21:27.788, +15:44:25.05 | 20.1 | 2.2 ± 0.1 | 65.8 ± 2.4 |

Notes.

$^{a}$ For simplicity of the region name, we chose one UCHII for the name prefix when there were two UCHIIs relevant to the [Fe ii] features.

$^{b}$ These values are inferred from near-infrared color excess. See Section 3.2 for detail.

$^{c}$ The extinctions were corrected, using corresponding $A_{\text{V}}$ and the extinction curve of “Milky Way, RV = 3.1” (Weingartner & Draine 2001; Draine 2003).
Figure 5. Comparison of [Fe\textsc{ii}] features with other near-infrared images: the continuum-subtracted [Fe\textsc{ii}] (top-panels), the H$_2$ $\nu = 1 \rightarrow 0$ S(1) 2.12 $\mu$m, K RGB composite image (middle panels; R = H$_2$, G = K, B = K), and the J, H, K RGB composite image (bottom panel; R = K, G = H, B = J). The field-of-view setting, boxes, and ellipses are the same as Figure 2. The H$_2$ (FWHM $\sim 0\arcsec.7$) and JHK images (FWHM $\sim 0\arcsec.8$) are from the UWISH2 (Froebrich et al. 2011) and UKIDSS (Lucas et al. 2008) surveys, respectively.

(A color version of this figure is available in the online journal.)

outflow velocity, and the inclination (see Section 3.2.3 of Shinn et al. 2013).

3.4.1. G025.3809$-$00.1815 and G025.3824$-$00.1812

The kinematic distances to the cluster W 42 where the two UCHIIs reside were estimated as follows: 3.8 kpc (Anderson & Bania 2009), 3.92 kpc (Jones & Dickey 2012), 4.0 kpc (Kolpak et al. 2003), 5 kpc (Radhakrishnan et al. 1972), 10.8 kpc (Churchwell et al. 1990), 13.4 kpc (Wilson 1972), and 13.5 kpc (Downes et al. 1980). The spectrophotometric distances were estimated to be 2.2 kpc (Blum et al. 2000) and 2.67 kpc (Moisés et al. 2011). The spectrophotometric distance suggests that
the UCHIIs are probably located at the near side among the two ambiguous kinematic distances. Therefore, we adopted a distance of 3.9 kpc, which is the average of near-side distances estimated within 10 yr.

3.4.2. G028.2879−00.3641

The kinematic distances were estimated to be 3.0 kpc (Churchwell et al. 2010; Anderson & Bania 2009) and 3.29 kpc (Cyganowski et al. 2009). We adopted 3.2 kpc, averaging these values.

3.4.3. G050.3152+00.6762 and G050.3157+00.6747

The kinematic distances were estimated to be 2.1 kpc (Watson et al. 2003), 2.16 kpc (Araya et al. 2002), 8.7 kpc (Churchwell et al. 1990), and 9.7 kpc (Anderson & Bania 2009). The extinction to these UCHIIs is about $A_V \sim 20$, which is more than 10 magnitudes higher than other UCHIIs located around 3–4 kpc (Table 1). We think the distance of $\sim 2.1$ kpc is unlikely to give such a high extinction. Therefore, we adopted 9.2 kpc, averaging the two larger estimations.
3.5. UCHII with nearby [Fe II] Outflow Features and the CORNISH Catalog Parameters

In this section, we investigate the relations between the [Fe II] outflow features and the CORNISH catalog parameters (Table 3). First, we contrast the location of the UCHIIs accompanying [Fe II] features in the plots of three UCHII parameters: angular scale, integrated flux density, and peak flux density. These three UCHII parameters are from the CORNISH catalog (Purcell et al. 2013), and Figure 6 shows their scatter plots. The plot of angular scale versus integrated flux density presents a rough correlation (black point). This correlation seems to reflect the distance effect on the UCHIIs of semi-uniform luminosity and physical size, which should show (angular scale) \( \sim \) (distance\(^{-1}\)) and (flux) \( \sim \) (distance\(^{-2}\)), and hence (angular scale) \( \sim \) (flux\(^{1/2}\)). The plot of angular scale versus peak flux density presents almost no correlation. This seems to be caused by the weakening of the distance effect, replacing the integrated...
Figure 6. UCHIIs scatter plot using the parameters from the CORNISH UCHII catalog. The points are the UCHII candidates from the CORNISH catalog which provides the angular scale, integrated flux density, and peak flux density. The squares and circles indicate the UCHIIs that show [Fe ii] outflow features and candidate features, respectively. The gray dashed lines in the left plot show the locus of \((\text{angular scale}) \sim (\text{integrated flux density})^{1/2}\).

Table 2
Outflow Mass-loss Rate Estimated from Dereddened [Fe ii] Flux

| Region                  | Velocity \(^b\) (km s\(^{-1}\)) | Distance \(^c\) (kpc) | Length \(^d\) (\(^{\prime\prime}\)) | Solid Angle \(^e\) \((10^{-11} \text{ sr})\) | Method \(^d\) | \(M_{\text{out}} \) \(^f\) \((10^{-6} M_\odot \text{ yr}^{-1})\) |
|------------------------|---------------------------------|-----------------------|---------------------------------|---------------------------------|----------------|-------------------------------------------------|
| G025.3809−00.1815−A    | 200                             | 3.9                   | ...                             | ...                             | Sh             | 4.44 ± 0.17                                     |
| G025.3809−00.1815−B    | 100                             | 3.9                   | ...                             | ...                             | Sh             | 16.40 ± 0.90                                    |
| G025.3809−00.1815−C    | 100                             | 3.9                   | ...                             | ...                             | Sh             | 39.00 ± 1.13                                    |
| G028.2879−00.3641−A    | 200                             | 3.2                   | ...                             | ...                             | Sh             | 1.36 ± 0.07                                     |
| G028.2879−00.3641−B    | 200                             | 3.2                   | ...                             | ...                             | Sh             | 3.32 ± 0.10                                     |
| G050.3152+00.6762−A    | 200                             | 9.2                   | 1.0                             | 4.3                             | St             | 8.87 ± 0.33                                     |

Notes.

\(^a\) For simplicity of the region name, we chose one UCHII for the name prefix when there were two UCHIIs relevant to the [Fe ii] features.

\(^b\) We adopted the outflow velocity of 100 km s\(^{-1}\) or 200 km s\(^{-1}\). See Section 3.4 for detail.

\(^c\) The distance is adopted from previous estimates. See Section 3.4 for detail.

\(^d\) “Sh” and “St” indicate the “Fe-Shell” and “Fe-Stream” methods used for the \(M_{\text{out}}\) estimation, respectively. See Section 3.4 for detail.

\(^e\) These values are subject to substantial uncertainties originating from the uncertain outflow velocity, extinction, Fe depletion, etc. See the text for details. The listed errors are from the [Fe ii] flux error only.

Table 3
UCHII Parameters from the CORNISH Catalog

| UCHII                  | Peak Flux Density \((\text{mJy beam}^{-1})\) | Integrated Flux Density \((\text{mJy})\) | Angular Scale \((^{\prime\prime})\) | Deconvolved Size \((^{\prime\prime})\) |
|------------------------|---------------------------------------------|------------------------------------------|----------------------------------|-----------------------------------|
| G013.8726+00.2818\(^a\) | 24.71 ± 2.21                               | 1447.55 ± 129.84                        | 15.430 ± 0.009                   | 15.4                              |
| G025.3809−00.1815      | 28.64 ± 2.57                               | 460.83 ± 42.66                         | 8.456 ± 0.013                    | 8.3                               |
| G025.3824−00.1812      | 36.62 ± 3.32                               | 200.13 ± 20.03                         | 3.436 ± 0.013                    | 3.1                               |
| G028.2879−00.3641      | 98.00 ± 8.73                               | 552.77 ± 51.90                         | 4.607 ± 0.005                    | 4.4                               |
| G050.3152+00.6762      | 46.28 ± 4.12                               | 81.31 ± 8.07                          | 2.107 ± 0.007                    | 1.5                               |

Note. \(^a\) This UCHII might have [Fe ii] features around it, but with a low plausibility (cf. Section 3.1 and Figure 3).

flux density with the peak flux density which is likely independent of the distance.

The UCHIIs accompanying [Fe ii] features occupy separate regions in Figure 6. This is more easily seen in the plot between peak flux density and angular size. The UCHIIs reside in the range of relatively higher peak flux density \((\sim 3 \times 10^{-1} \times 10^{2} \text{ mJy beam}^{-1})\) regardless of angular scale.
3.6. Point Sources with Near-infrared Excess around UCHIIs

We are looking for the “footprint” outflow features around UCHIIs which were produced by the material ejected during the past, active accretion phase of MYSOs. However, considering that massive stars usually form in clusters which include numerous other YSOs (Zinnecker & Yorke 2007, and references therein), the outflow features can also be produced by other YSOs. In order to examine the population of YSOs near the UCHIIs, we investigated the near-infrared color excess of nearby point sources.

Figure 7 shows the color–color diagram of \((J − H)\) versus \((H − K)\) and the corresponding composite image of \(H\) and \([\text{Fe} \text{ii}]\). We use the photometry data from the UKIDSS (Lawrence et al. 2007) GPS (Lucas et al. 2008), except for G028.2879–00.3641. The UKIDSS GPS do not provide the \(J\)-band photometry for G028.2879–00.3641, and hence we instead used the photometry data from 2MASS (Skrutskie et al. 2006) which has inferior spatial resolution and survey depth to UKIDSS GPS (Lawrence et al. 2007). In the color–color diagram, we plot the locus of the main-sequence stars employing the values in Hewett et al. (2006). For the 2MASS data, we transformed the locus using the equation in Hewett et al. (2006). The extinction line was calculated using the results of Rieke & Lebofsky (1985).

We classify the point sources that reside below the extinction line as showing the near-infrared excess. As Figure 7 shows, there are several point sources with near-infrared excess around UCHIIs. These sources could be YSOs, and they could potentially produce the \([\text{Fe} \text{ii}]\) outflow features observed around UCHIIs.

4. DISCUSSION

4.1. Nature and Origin of the \([\text{Fe} \text{ii}]\) Features around UCHIIs

We seek the “footprint” outflow features around UCHIIs which are produced by the material ejected during the prior, active accretion phase of MYOS. The \([\text{Fe} \text{ii}]\) 1.644 \(\mu\)m emission line was employed, and we found that 5 out of 237 UCHIIIs have nearby \([\text{Fe} \text{ii}]\) features. Based on the given observational facts and estimations, it seems that the detected \([\text{Fe} \text{ii}]\) features might be the “footprint” outflow features, but more detailed and targeted study is required to clarify it. More specific points are given below.

First, the morphological relation between the \([\text{Fe} \text{ii}]\) and 5 GHz radio continuum features is compatible with the “footprint” interpretation. The radio features are elongated toward the \([\text{Fe} \text{ii}]\) features in the cases of G025.3809–00.1815 (Figure 2(a)) and G028.2879–00.3641 (Figure 2(b)). The candidate G013.8726+00.2818 (Figure 3) also shows a similar morphological relation. Only G050.3152+00.6762 (Figure 2(c)) does not show such a relation. However, considering that the \([\text{Fe} \text{ii}]\) features near G050.3152+00.6762 could be produced by the other UCHII G050.3157+00.6747, all the facts suggest a relation between the \([\text{Fe} \text{ii}]\) and radio continuum features.

This morphological relation can be understood in the disk-accreting MYSO model (e.g., Yorke & Sonnhalter 2002; Krumholz et al. 2009; Kuiper & Yorke 2013a), which has a bipolar cavity excavated by the radiation pressure and outflow materials. The cavity structure is seen up to the radial distance of \(\sim 2 \times 10^4\) AU \(\sim 0.1\) pc, which is comparable to the typical size of a UCHII (Wood & Churchwell 1989; Hoare et al. 2007). The ionized gas would expand more rapidly through the cavity, and hence the morphology of the ionized gas would be extended along the cavity direction, i.e., the outflow direction. The diffuse near-infrared continuum features seen northeast from G025.3809–00.1815 and G025.3824–00.1812 (Figure 2(a)) likely emanated through such a cavity. Also, the high-velocity CO gas mapped in the study of Shepherd & Churchwell (1996) is probably from the bipolar outflows following the cavity.

Second, \(M_{\text{out}}\) does not provide a clear answer as to whether or not the \([\text{Fe} \text{ii}]\) features are the “footprint” outflow features. \(M_{\text{out}}\) is estimated to be \(\sim 1 \times 10^{-6} \times 10^{-5} M_\odot\) yr\(^{-1}\) (Table 2). If we assume a typical ratio between the outflow mass-loss rate and the disk accretion rate \(M_{\text{out}}/M_{\text{acc}} = 0.1\) (Ellerbroek et al. 2013; Ray et al. 2007; Frank et al. 2014), then we can guess \(M_{\text{out}}\) from \(M_{\text{acc}}\) of MYSO models. The \(M_{\text{acc}}\) of MYSO models ranges from \(\sim 10^{-4} \times 10^{-3} M_\odot\) yr\(^{-1}\) (e.g., Yorke & Sonnhalter 2002; Krumholz et al. 2009, 2012; Kuiper & Yorke 2013b), and hence \(M_{\text{out}}\) would be around \(\sim 10^{-5} \times 10^{-4} M_\odot\) yr\(^{-1}\). Our \(M_{\text{out}}\) estimation is overlapped with this model-inferred \(M_{\text{out}}\), but a little lower. Meanwhile, \(M_{\text{out}}\) is comparable to the \(M_{\text{out}}\) of low- or intermediate-mass YSOs such as the Herbig Ae/Be star and FU Ori object (Ellerbroek et al. 2013). We therefore cannot exclude the possibility that the observed \([\text{Fe} \text{ii}]\) features were produced by nearby low- or intermediate-mass YSOs.

Third, the travel time of the \([\text{Fe} \text{ii}]\) features does not exclude the “footprint” interpretation, although the time is roughly estimated. If the outflow material that excites the \([\text{Fe} \text{ii}]\) features is ejected from the location of a UCHII, we can guess the time the material spent to arrive at the \([\text{Fe} \text{ii}]\) feature position. We adopted the velocity and the distance listed in Table 2, and assumed the outflow material flowing on the plane of the sky. The travel time is estimated to be \(\sim (1–8) \times 10^3\) yr (Table 4). These times are shorter than the typical lifetime of UCHIIIs (\(\sim 5 \times 10^4\) yr, Wood & Churchwell 1989; González-Avilés et al. 2005) and the MYSO jet phase (\(\sim 4 \times 10^4\) yr; Mottram et al. 2011; Guzmán et al. 2012). Therefore, depending on when the outflow was launched, the \([\text{Fe} \text{ii}]\) feature can be interpreted as the “footprint” or even as having been excited by the outflow launched during the UCHII phase. We note that some studies assert that there is ongoing accretion onto the central object even after the H II region development (Keto 2002, 2003; Keto & Wood 2006; Keto & Klaassen 2008). For reference, we calculated the expansion time of UCHIIIs (Table 4) using the typical sound velocity of the H II region and the deconvolved size of UCHIIIs (Table 3). Both the expansion and travel times have a similar order of magnitude. The adopted sound velocity is \(c_s = \sqrt{\gamma k T / \mu m_H} \sim 15\) km s\(^{-1}\) with \(\gamma = 5/3, \mu = 0.61,\) and \(T = 10^4\) K. We note that the travel time can be longer if the inclination to the plane of sky is allowed for. The outflow velocity is definitely another element that can make the time shorter or longer.

### Table 4

| UCHII | H II Region Expansion Time (10\(^3\) yr) | Outflow Travel Time (10\(^3\) yr) |
|-------|---------------------------------------|----------------------------------|
| G025.3809–00.1815 | 5.1 | 4.0–6.1\(^b\) |
| G025.3824–00.1812 | 1.9 | 4.7–7.6\(^b\) |
| G028.2879–00.3641 | 2.2 | 1.0–1.1\(^b\) |
| G050.3152+00.6762 | 2.2 | 1.3 |

**Notes.**

\(^a\) These quantities are estimated with several assumptions. See Section 4.1 for detail.

\(^b\) The time is estimated for all the relevant \([\text{Fe} \text{ii}]\) features (cf. Figure 2).
Fourth, several YSO candidates existing near the UCHIIs hinder the “footprint” interpretation. As Figure 7 shows, there are several point sources that have near-infrared color excesses near the UCHIIs. If these sources are YSOs, then they could have produced the observed $\text{[Fe \text{II}] kont}$ features. For example, the YSO candidates close to the cataloged UCHII position could have done so (Figure 7(a) and (b)), and the YSO candidate on the symmetric position of UCHII about the $\text{[Fe \text{II}] kont}$ feature could also have done so (Figure 7(c)). The three points argued above—morphology, $M_{\text{out}}$, and travel time—can be understood without the “footprint” interpretation if the YSO candidates near UCHIIs can produce $M_{\text{out}}$ of $\sim 1 \times 10^{-6} - 4 \times 10^{-5} M_\odot \text{ yr}^{-1}$, like the Herbig Ae/Be star or FU Ori objects (Ellerbroek et al. 2013). In that case, the travel time of $\sim (1–8) \times 10^3 \text{ yr}$ (Table 4)
is not contradictory to the typical lifetime of a Herbig Ae/Be star (a few Myr, Waters & Waelkens 1998) or an FU Ori object (~0.1 Myr, Hartmann & Kenyon 1996).

4.2. [Fe ii] Feature Detection and UCHII Parameter

Figure 6 shows that the UCHIIIs accompanying [Fe ii] features reside over the relatively higher range of peak flux density (~3 × 10^−1 to 10^2 mJy beam^−1), regardless of the angular size. Considering that the peak flux density would decrease as the UCHII expands, this distribution indicates that the [Fe ii] features are more likely produced around younger UCHIIIs. This is reasonable, because younger UCHIIIs would disperse less nearby natal clump materials and would increase the chance of collision between the outflow and natal clump materials.

Out of 237 UCHIIIs, 5 showed nearby [Fe ii] features. For comparison, we note the ~90% detection rate of high-velocity CO gas around 94 UCHIIIs observed in radio (Shepherd & Churchwell 1996). Also, Varricatt et al. (2010) detected H2 features around 4 of 13 UCHIIIs, imaging the H2 ν = 1 → 0 S(1) 2.12 μm emission line. The H2 ν = 1 → 0 S(1) line is well excited by far-UV radiation (Hollenbach & Tielens 1997), and hence we should be careful in interpreting these H2 features as outflow features. If these H2 features are outflow features, then the overall CO, H2, and [Fe ii] detection rates can be understood with the probability distribution of the outflow velocity. In order to be excited, CO, H2, and [Fe ii] require shock velocities of increasing magnitude. Therefore, if the outflow velocity distribution has a higher probability at a lower velocity, then the CO, H2, and [Fe ii] detection rates of decreasing order can be explained.

One possible reason for the low [Fe ii] detection rate is the extinction toward UCHIIIs, which is typically AV ≥ 30–50 (Hanson et al. 2002) ~ AV ≥ 6–9 (Draine 2003). Therefore, we may miss numerous [Fe ii] features. Note that AV for three UCHIIIs in Table 1 are relatively low (AV ~ 9–20). Another possible reason is that the outflow cavity is already open to the outside of the natal clump (see Kim & Koo 2001), and hence less materials exist to collide with the outflow. The typical size of clumps (~0.3–3 pc, Bergin & Tafalla 2007) is smaller than the traveling distance of a 100–200 km s^−1 outflow material over the typical lifetime of a MYSO jet-phase (~10^4 yr, Mottram et al. 2011; Guzmán et al. 2012). If the outflow direction is steady, then it would make the situation worse. Another possible reason is the weakness of [Fe ii] features. The shocked [Fe ii] features are likely to be unresolved and the [Fe ii] flux is proportional to the column density along the line of sight. Hence, weak [Fe ii] features from low column density might not have been detected due to the detection limit. The UWIFE survey has a nominal 5σ detection limit of ~18.7 mag for point sources (Lee et al. 2014). The low outflow velocity is another possible reason. If the outflow material is ejected with a velocity too low to produce a J-type shock (see Draine & McKee 1993; Le Bourlot et al. 2002) over a certain amount of time, e.g., low accretion duration, then the chance of seeing the [Fe ii] feature is reduced. Finally, if the outflow material is clumpy or bullet-like rather than continuous stream-like, then the chance to observe a shocked [Fe ii] feature would be lower, depending on the emergence frequency of the outflow material. The observed [Fe ii] features appear to be both stream-like (Figure 2(c)) and clumpy (Figure 2(b)) outflow materials. More observations for the weaker [Fe ii] features would help to assess the effects of outflow type on [Fe ii] feature detection.

5. CONCLUSIONS

We sought the “footprint” outflow features around UCHIIIs which are produced by materials ejected during the past, active accretion phase of MYSOs. The UWIFE survey data (Lee et al. 2014) and the CORNISH UCHII catalog (Hoare et al. 2012; Purcell et al. 2013) were employed for the search. The UWIFE survey is an imaging survey of the [Fe ii] 1.644 μm emission line, and the CORNISH survey is a 5 GHz radio continuum survey, both of which cover the first Galactic quadrant. Typical seeing for the two surveys is ~0.8 (UWIFE) and ~1.5 (CORNISH), respectively.

Of the 237 UCHIIIs, 5 showed nearby [Fe ii] features, 1 of which was less plausible and was tagged as a candidate. We propose that these [Fe ii] features might be the “footprint” outflow features we are searching for, but more detailed and targeted
study is required to clarify whether or not this is true. This is based on the following observational facts and estimations: the morphological relation between the $\text{[Fe ii]}$ and $5\text{GHz}$ radio features, $M_{\text{out}}$ estimated from the $\text{[Fe ii]}$ flux, the travel time of the $\text{[Fe ii]}$ features, and the existence of several YSO candidates near the UCHIIs. The UCHIIs accompanying the $\text{[Fe ii]}$ features have a relatively higher peak flux density in $5\text{GHz}$.

The fraction of UCHIIs accompanying the $\text{[Fe ii]}$ features, $5/237$, is small compared to the $\sim 90\%$ detection rate of high-velocity CO gas around UCHIIs. We discuss the reasons for this low detection rate, including the extinction, the configuration of the outflow cavity, the weakness of $\text{[Fe ii]}$ features, the low outflow velocity, and the outflowing type. We note that the sub-arcsec interferometric observations of CO rotational lines would be useful in studying the “footprint” outflow features, considering its high detection rate.

J.-H.S. is grateful to Melvin Hoare and Stuart Lumsden for the discussion on the results. H.-J.K. was supported by an NRF (National Research Foundation of Korea) grant funded by the Korean Government (NRF-2012-Fostering Core Leaders of the Future Basic Science Program). B.-C.K. was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MISP) (No. 2012R1A4A1028713). J.-H.S. is grateful for the referee’s comments which improved the manuscript.

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