HIGH SPATIAL RESOLUTION SPECTROSCOPY OF W51 IRS 2E AND IRS 2W: TWO VERY MASSIVE YOUNG STARS IN EARLY FORMATION STAGES

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ABSTRACT

We present K-band spectra of the near infrared counterparts to IRS 2E and IRS 2W which is associated with the ultracompact H II region W51d, both of them embedded sources in the Galactic compact H II region W51 IRS 2. The high spatial resolution observations were obtained with the laser guide star facility and Near-infrared Integral Field Spectrograph (NIFS) mounted at the Gemini-North observatory. The spectrum of the ionizing source of W51d shows the photospheric features N III (21155 Å) in emission and He II (21897 Å) in absorption which lead us to classify it as a young O3 type star. We detected CO overtone in emission at 23000 Å in the spectrum of IRS 2E, suggesting that it is a massive young object still surrounded by an accretion disk, probably transitioning from the hot core phase to an ultracompact H II region.

Subject headings: infrared: stars — stars: early-type — stars: formation — techniques: spectroscopic

1. INTRODUCTION

The mechanisms of massive star formation ($M_{*} > 10 M_{\odot}$) are the subject of intense discussion even after two decades of great progress and improvement of observational techniques. In the last two decades, the development of larger and more sensitive infrared detectors associated with the commissioning of 8 m class telescopes equipped with adaptive optics has made it possible to observe ever deeper into the sites of massive star formation at relatively short wavelengths. Yet, while all these improvements have contributed to our understanding of massive star formation, the basic process, i.e., formation via an accretion disk, coalescence, competitive accretion, or a combination of these, is still unknown (for a review on this discussion see Zinnecker & Yorke 2007). The Spitzer Space Telescope is providing an unprecedented view at longer wavelengths and soon the Herschel Space Observatory and ALMA will combine very high sensitivity and angular resolution to probe the earliest phases of massive star formation.

W51 is one of the most luminous complexes of massive star-forming regions in the Galaxy (Goldader & Wynn-Williams 1994) with multiple H II regions (Wilson et al. 1970) that host at least six H II regions with embedded clusters, all of them optically obscured (Kumar et al. 2004). The most luminous of all H II regions is G49.5−0.4 which can be resolved into mainly two bright infrared sources: IRS 1 and IRS 2, which are coincident with radio sources W51e and W51d, respectively (Martin 1972). IRS 2 is a compact H II region harboring three ultracompact H II (UC H II) regions W51d, W51d1, and W51d2 (Mehringer 1994) and a plethora of infrared sources (Goldader & Wynn-Williams 1994; Okumura et al. 2001; Okamoto et al. 2001; Kramer et al. 2001; Figuereôdo et al. 2008; C. L. Barbosa et al. 2008, in preparation). The most prominent sources in the K band are named IRS 2 East and IRS 2 West (or IRS 2E and IRS 2W, respectively, for short). IRS 2W was identified as a NIR and MIR peak of nebular emission (Goldader & Wynn-Williams 1994) and Okamoto et al. (2001) have correlated it with the UC H II region W51d.

In this Letter we report the results of spectroscopic observations taken with laser guide star (LGS) adaptive optics of IRS 2E and the UC H II region W51d (IRS 2W). In the § 2 we report the technical details of the observations and in the § 3 we report and discuss the results. Finally, in the § 4 we summarize our conclusions.

2. OBSERVATIONS

The data were obtained with the Near-infrared Integral Field Spectrograph (NIFS) mounted on the Frederick C. Gillett 8 m telescope at the Gemini-North observatory on Mauna Kea, Hawaii, in queue mode on 2007 May 4 under program ID GN-2007A-Q-34. NIFS provides 2D integral field spectroscopy with $R \sim 5200$ over a $3 \times 3$ field of view with $0.043'' \times 0.10''$ rectangular “pixels.” Also, we used the Gemini-North adaptive optics system Altair with a LGS to achieve an angular resolution of $<0.2''$ measured on the 2D images built from the data cubes.

The observations were carried out with the standard procedures for the near-infrared (NIR): we observed IRS 2 in a series of three pointings of 1000 s on-source and 1000 s on a “blank” sky position at $\sim 10''$ north of IRS 2 for each field. The latter image was used to subtract the sky emission from the images of the targets. We also observed the A0 V star HIP 98640 with air mass similar to that of IRS 2 in order to remove the telluric absorption lines from the spectra of the observed targets. The spectra of A0 V stars show only the Brγ feature in absorption in the K band. We eliminated this feature by fitting a Voigt profile to the Brγ leaving a spectrum with only telluric absorption features. This telluric spectrum was used to correct the spectra of the targets.

Wavelength calibration was achieved with an exposure of an argon arc lamp obtained with the Gemini calibration module GCAL. All data were precessed in the IRAF environment with scripts written for NIFS available through the Gemini IRAF.
package. We extracted the spectra through a 0.4″ circular aperture centered on the sources. This aperture was chosen to minimize the contribution of the nebular emission from the H II region.

We show in Figure 1 the finding chart of IRS 2. It is composed by the high-resolution image taken with the adaptive optics NIR camera NACO in the K band. This image is available at the ESO public database. We overplotted the radio continuum emission at 2 cm from Wood & Churchwell (1989) in white contours. The black contours represent the MIR emission at 12 μm from the Gemini-South MIR camera T-ReCS. All NIFS pointings are represented by white squares and the sources which have spectra are labeled. In the following section we present the results of the observations of IRS 2E and the UC H II region W51d in the “pseudo-long-slit” mode extracted from the images delivered by NIFS. A complete analysis of these data, including the spectra of all observed sources and the results from the IFU mode, such as the velocity maps of the regions observed, will be presented in a forthcoming paper (C. L. Barbosa et al. 2008, in preparation).

3. RESULTS AND DISCUSSION

3.1. IRS 2E

Figure 2 shows the spectrum of IRS 2E, the brightest K-band source in the compact H II region. It was obtained from the first pointing of the telescope. The continuum shows a steep, rising slope to longer wavelengths reflecting the fact that this source is under heavy extinction: AV ∼ 63 mag according to our unpublished MIR data. This high extinction makes IRS 2E undetected at wavelengths shorter than 16000 Å.7 The spectrum of Figure 2 shows strong lines of He i (20587 Å) and unresolved Brγ (21661 Å) that may arise from the circumstellar gas heated by hot stars. We also note nebular lines of He i (21127 Å) and the Hg [1–0 S(1), 21218 Å] that come from the diffuse nebular emission of the H II region. Previous authors (e.g., Okumura et al. 2001; Figuerêdo et al. 2008) describe the presence of [Fe II] lines in the spectrum of IRS 2E. These emission lines are typical of shocked gas in the vicinity of massive young stellar objects (MYSOs; Hanson et al. 2002; Bik et al. 2006). The spectrum in Figure 2 does not show any of these lines. This is due to the small aperture used to extract the spectrum. Actually, our unpublished line maps show that [Fe II] emission comes from the extended region between IRS 2E and OKYM 2/KID 5.

More interesting, IRS 2E shows CO overtone emission, as we detected the (2–0), (3–1), (4–2), and (5–3) band heads between 22935 and 23838 Å. Previous NIR spectroscopy of IRS 2E (e.g., Okumura et al. 2001; Figuerêdo et al. 2008) could not detect the CO band head emission due to the large contribution of nebular emission through wide and long slits.

The detection of the CO overtone in emission is associated with the presence of an accretion disk, both in low-mass (e.g., Najita et al. 1996) and high-mass YSOs (Bik & Thi 2004; Blum et al. 2004). The CO overtone emission comes from the inner parts a circumstellar disk, in regions of high column densities (10^{20}–10^{21} cm^{-2}) and temperatures between 1500 and 4500 K.

IRS 2E is a deeply embedded source which is bright at wavelengths longer than 20000 Å and is not associated with any UC H II region. These characteristics are those expected for a very young and massive YSO that is transitioning to an UC H II region; the high accretion rate presumably prevents the formation of an UC H II region as the ionized gas near the source falls onto the star, according to the evolutionary scenario proposed by Churchwell (2002). This class of object was observed in NGC 3576 by Barbosa et al. (2003) for example.

3.2. W51d

Figure 3 shows the spectrum of the UC H II region W51d. Treated as a peak of nebulosity in the NIR by Goldader & Wynn-Williams (1994), a stellar object was identified by Figuerêdo et al. (2008) as responsible for the ionization of this region based on the correlation between the radio and MIR emission presented by Okamoto et al. (2001) and the new high-resolution images obtained by us or collected at public databases.

The spectrum of W51d was normalized and enlarged near the intense Brγ line to better show the detected features. This line has a broad component (∼700 km s^{-1}) probably originating in fast winds coming from the hot ionizing star, and two scenarios are possible to explain it. In the first case, the very young star has strong winds that blew away its surrounding dust. In

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7 Unpublished images obtained from the AO assisted camera NACO at the VLT shows that the source detected at the J band by previous authors is just a bright knot of gas.
the second case, the ionizing star is still surrounded by a torus that is seen more face on. However, only higher resolution data could favor one of these scenarios. Besides this nebular line, that is seen more face on. However, only higher resolution data in this case, the ionizing star is still surrounded by a torus (such as hot core (such as main-sequence stars and may be more reliable for W51d, given its young age. Finally, we used the radius for other photons are in mind the limitations of this method, since it assumes that all photons emitted in the Lyman continuum are effectively ionizing the gas, and this may not be true as explained in the previous section. Some amount of the total number of photons may be escaping the UC H II region while other photons are destroyed by dust.

Starting with equation (4) given by Kurtz et al. (1994) (\(\xi = 1\), i.e., all photons in the Lyman continuum effectively ionize the gas) we obtain the distance \(d\) (in kpc) as a factor of the electron temperature \(T_e\), the correction factor \(\alpha(\nu, T_e)\), the frequency \(\nu\), and the flux density \(S_n\) as

\[
d^2 = 1.32 \times 10^{-49} N_e \frac{\alpha(\nu, T_e)}{S_n(\text{Jy})} \left(\frac{\nu}{\text{GHz}}\right)^{-0.1} \left(\frac{T_e}{\text{K}}\right)^{0.5}.
\]

The critical parameter in the above equation is the number of photons emitted in the Lyman continuum \(N_e\). Values for that parameter can vary an order of magnitude depending on which author is quoted. We derived \(N_e\) as follow: for spectral types ranging from an O3 to an O4 star at the zero-age main sequence (ZAMS) we took their effective temperature from Table 1 of Martins et al. (2005): 44,616 K for an O3 and 43,419 K for an O4 star. Using the Geneva models of Schaller et al. (1992) we obtained the bolometric magnitude \(M_{bol}\) for each star in the ZAMS (\(-8.94, O3\) and \(-8.7, O4\)). We derived the stellar radius from the effective temperature above and its corresponding luminosity: 5.476 and 9.2 \(R_\odot\) for an O3 and 4.638 and 8.7 \(R_\odot\) for an O4 star. The radius and the luminosity calculated for a star in the ZAMS are significantly smaller than those quoted for main-sequence stars and may be more reliable for W51d, given its young age. Finally, we used the radius for each star to obtain the number of ionizing photons emitted per unit time from equation (9) of Martins et al. (2005), and the ionizing fluxes \(Q_\odot\) for each respective effective temperature quoted in the Table 1 of that paper. According to these procedures an O3 star can produce \(1.86 \times 10^{49}\) s\(^{-1}\) and an O4, \(1.44 \times 10^{49}\) s\(^{-1}\) in the ZAMS.

Returning to our equation (1), \(S_n\) and \(T_e\) quoted for W51d are 5.35 Jy and \(10^4\) K at \(\nu = 15\) GHz (Wood & Churchwell 1989) and \(\alpha(\nu, T_e) = 0.9767\) Mezger & Henderson (1967). The radio flux of W51d is blended with that of W51d, in data presented by Mehringer (1994) so it is overestimated and therefore cannot be used. The results are as follows: for a ZAMS O3 star, \(d = 5.8\) kpc and for an ZAMS O4, \(d = 5.1\) kpc. We can compare our results with those obtained using the number of ionizing photons given by Martins et al. (2005) for main-sequence stars; in this case the distance is 8.8 kpc for an O3 V and 7.4 kpc for an O4 V star.

We cannot take these results at their face value, given the limitations of the method described above. However, the results

![Fig. 3.—K-band spectrum of source W51d. This spectrum was zoomed to show the N II multiplet and He II. The thin line near 20587 Å is a residual feature produced after the correction of the telluric lines.](image-url)
can be used as upper limits to the distance to IRS 2. The distance to W51 North, which may be associated with IRS 2, quoted in the literature was obtained through observations of proper motions of water masers and amounts to 8.3 (± 2.5) kpc (Schnepp et al. 1981) or 6.1 (± 1.3) kpc (Imai et al. 2002). The upper limits obtained above are compatible (within the errors) with those obtained from the water masers if we consider the ionizing star of W51d an O3–O4 star in the ZAMS. However, these upper limits would make IRS 2 part of W51 Main, just as an effect of projection on the sky, given the distance of 2 kpc obtained with spectroscopic parallax by Figuerêdo et al. (2008).

4. CONCLUSIONS

We presented K-band spectra of the embedded sources IRS 2E and IRS 2W/W51d in the compact H ii region IRS 2. The high angular resolution achieved by NIFS and Altair made possible the separation of the strong extended emission from the emission of the MYSO itself. It has proved a valuable tool in the study of MYSOs, as can be seen in our summary of the results presented in the previous sections:

1. We identified the ionizing source of the UC H ii region W51d as a massive star earlier than about type O4 based on the N iv multiplet (in emission), the He ii line (in absorption), and the absence of C iv in emission.

2. We detected compact (unresolved) CO overtone emission toward source IRS 2E for the first time, suggesting the presence on an accretion disk around this source. The absence of radio emission and the presence of an accretion disk indicate that IRS 2E is a massive YSO.

3. Combining the spectroscopy of W51d and its radio data, we found an upper limit to the distance to IRS 2 between 5.1 and 5.8 kpc for an ionizing star of spectral type between O3 and O4 in the ZAMS.

The fact that we detected two very massive stars, close in space, one which has cleared its surrounding material enough to probe its photosphere and another in a younger phase, deeply embedded in its dust cocoon and still surrounded by a disk, indicates that the evolutionary timescale of MYSOs is extremely short.

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