EXTREMELY BROAD RADIO RECOMBINATION MASER LINES TOWARD THE HIGH-VELOCITY IONIZED JET IN CEPHEUS A HW2

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Abstract

We present the first detection of radio recombination lines (RRLs) at millimeter wavelengths toward the high-velocity ionized jet in the Cepheus A HW2 star-forming region. From our single-dish and interferometric observations, we find that the measured RRLs show extremely broad asymmetric line profiles with zero-intensity line widths of ∼1100 km s⁻¹. From the line widths, we estimate a terminal velocity for the ionized gas in the jet of 500 km s⁻¹, consistent with that obtained from the proper motions of the HW2 radio jet. The total integrated line-to-continuum flux ratios of the H40α, H34α, and H31α lines are 43, 229, and 280 km s⁻¹, clearly deviating from LTE predictions. These ratios are very similar to those observed for the RRL masers toward MWC349A, suggesting that the intensities of the RRLs toward HW2 are affected by maser emission. Our radiative transfer modeling of the RRLs shows that their asymmetric profiles could be explained by maser emission arising from a bi-conical radio jet with a semi-opening angle of 18°, electron density distribution varying as r⁻², and turbulent and expanding wind velocities of 60 and 500 km s⁻¹.

Key words: ISM: individual objects (Cepheus A) – ISM: jets and outflows – masers – stars: formation

1. INTRODUCTION

Radio recombination lines (RRLs) are excellent probes of the kinematics of the ionized gas in ultracompact (UC) H II regions (Garay 1990; Churchwell et al. 1990). These lines typically show simple Gaussian profiles with line widths of 25–30 km s⁻¹, attributed to unresolved gas motions and/or pressure broadening (Gaume et al. 1995; Afflerbach et al. 1996; Kato et al. 2008). In addition to the classical UC H II regions with simple narrow (∼30 km s⁻¹) Gaussian RRLs, Jaffe & Martín-Pintado (1999) reported that 30% of the observed UC H II regions show even broader RRL emission with line widths of 70–200 km s⁻¹. These sources have power-law continuum spectra with spectral indices ∼0.6 (characteristic of constant velocity stellar winds; Olshon 1975), and elongated/bipolar morphologies resembling ionized flows. Jaffe & Martín-Pintado (1999) proposed that broad RRL emission could arise from bipolar ionized winds generated in photoevaporating neutral disks (Hollenbach et al. 1994; Gorti & Hollenbach 2009).

MWC349A is the best studied object with broad H recombination lines at optical, IR, centimeter, and millimeter wavelengths (Hartmann et al. 1980; Hamann & Simon 1986; Altenhoff et al. 1981; Martín-Pintado et al. 1989). This source, which has a rotating edge-on disk with a bipolar ionized flow (Cohen et al. 1985), is unique in its category because its RRLs at λ ≤ 2 mm (quantum numbers n < 35) are masers (optical depths < 1; Martín-Pintado et al. 1989, 1994). The RRL maser spots are located on the ionized surface of the disk (Planesas et al. 1992; Weintroub et al. 2008; Martín-Pintado et al. 2011), where the densities of the ionized gas are high enough (≥10⁶ cm⁻³) to invert the population of the levels involved in the RRL (Walmsley 1990). Although these masers are expected to be found in other UC H II regions (Martín-Pintado 2002), MWC349 is the only object where this emission has been reported so far in star-forming regions.

We present the first detection of RRL maser emission toward the Cepheus A HW2 high-mass star-forming region. This source shows a collimated, high-velocity ionized jet, with a continuum spectral index of ∼0.6 (Rodríguez et al. 1994). Like MWC349A, the molecular material around HW2 is mainly distributed in a neutral circumstellar disk (Patel et al. 2005; Jiménez-Serra et al. 2009) that seems to be photoevaporating (Jiménez-Serra et al. 2007). The proper motions of the HW2 radio jet suggest an expanding velocity for the outflowing gas of 500 km s⁻¹ (Curiel et al. 2006). This is consistent with the extremely broad line profiles (zero-intensity line widths of ∼1100 km s⁻¹) of the H40α, H34α, and H31α maser lines detected in our single-dish and interferometric observations. Cepheus A HW2 is the second RRL maser object detected to date in star-forming regions.

2. OBSERVATIONS

The H40α line at ∼99 GHz was observed toward Cepheus A HW2 with the IRAM Plateau de Bure Interferometer (PdBI) in the D configuration (beam of 5" × 4.5", P.A. = 91°). The phase center was set at α(J2000) = 22°56′17″, δ(J2000) = +62°01′49″. The wide-band correlator WideX provided a continuous frequency coverage of 3.6 GHz and a spectral resolution of 1.95 MHz (i.e., a velocity coverage and resolution of ∼10,900 km s⁻¹ and ∼6 km s⁻¹, respectively). 3C454.3 (23 Jy) and 3C273 (12 Jy) were used as bandpass calibrators. We observed MWC349A (1.2 Jy) and 1749+096 (2 Jy) as flux calibrators, and 0016+731 (0.6 Jy) and 2146+608 (0.3 Jy) as phase calibrators. Data reduction, calibration, imaging, and cleaning were performed with the GILDAS software.

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See http://www.iram.fr/IRAMFR/GILDAS.
The H34α line at \(~160\) GHz was detected toward HW2 with the IRAM 30 m telescope in a single-pointing observation during 140 minutes. The EMIR E1 receiver was tuned to single sideband with rejection of \(\geq 10\) dB. The beam size was \(15''\). The wide-band auto-correlator WILMA provided a total bandwidth and spectral resolution of \(4\) GHz and \(2\) MHz (∼\(6700\) km s\(^{-1}\) and \(3.7\) km s\(^{-1}\), respectively). Typical system temperatures were \(200–225\) K. Intensities were calibrated in \(T^*\) and converted into total flux (Jy) by using \(S/T^*=6.4\) Jy K\(^{-1}\)\(^{1.6}\).

The H31α line at \(210\) GHz was imaged toward HW2 with the Submillimeter Array (SMA) in the subcompact configuration (beam of \(4'8 \times 3'8\), P.A. = \(21\)°).\(^7\) The correlator setup provided a total bandwidth of \(4\) GHz per sideband and a spectral resolution of \(0.8\) MHz. This corresponds to a velocity coverage of \(\sim 5700\) km s\(^{-1}\) and a velocity resolution of \(1.1\) km s\(^{-1}\). 3C279 was used as bandpass calibrator; MWC349A, as flux calibrator (1.8 Jy); and 0102+584 (1.1 Jy) and BLLAC (5 Jy), as gain calibrators. Data calibration was performed within the MIR IDL package, while imaging and cleaning was done with MIRIAD.

3. RESULTS

In Figure 1 (upper panels), we present the full spectra measured toward Cepheus A HW2 at the wavelengths of the H40α, H34α, and H31α RRLs and smoothed to a velocity resolution of \(\sim 6\) km s\(^{-1}\). Since the HW2 radio jet is unresolved in the PdBI and SMA images (size of \(< 2''\); Rodríguez et al. 1994; Curiel et al. 2006), the H40α and H31α spectra were averaged within the \(5''\) beam of the PdBI and SMA observations. The measured RRL spectra (Figure 1) show three different features: (1) a strong slope due to the increase of the dust continuum emission with frequency \(\left(\propto \nu^{\alpha}\right)\), (2) a forest of narrow molecular lines arising mainly from the HC source in HW2 (Martín-Pintado et al. 2005; Jiménez-Serra et al. 2009), and (3) three faint and extremely broad features extending in velocity from \(\sim -500\) km s\(^{-1}\) to \(\sim 600\) km s\(^{-1}\) (zero-intensity line widths of \(\sim 1100\) km s\(^{-1}\)).

From the slope in the RRL spectra, we derive spectral indices for the continuum emission of \(\sim 2\), consistent with that calculated by Comito et al. (2007). The PdBI and SMA indices were obtained after subtracting the spectral energy distributions of the bandpass calibrators 3C454.3, 3C273, and 3C279. The derived continuum (dust+free–free) level at the frequencies of the H40α and H31α RRLs is \(\sim 0.12\) and \(0.69\) Jy, respectively. For the H34α line, this level was affected by an

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6 See [http://www.iram.es/IRAMES/mainWiki/Iram30mEfficiencies](http://www.iram.es/IRAMES/mainWiki/Iram30mEfficiencies).

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anomalous diffraction within the E1 receiver, although this did not affect the observed continuum slope and molecular line flux. The 2 mm continuum level (∼0.37 Jy) is estimated from the measured 3 mm and 1.4 mm continuum fluxes (Column 9 in Table 1).

From Figure 1, it is clear that molecular line confusion becomes an issue in this kind of studies, since multiple line blending could generate broad features mimicking broad emission from RRLs. Molecular lines from species such as SO2, C2H2CN, HC3N, or C2H5OH are identified at frequencies close to the RRLs (lower panels in Figure 1). However, their line widths are narrow (∼4–8 km s⁻¹), and the resulting blending features do not exceed ∼100 km s⁻¹. Note that other blending features are also found across the RRL spectral bands, with similar widths. It is then unlikely that line blending is responsible for the extremely broad emission, with zero-intensity line widths of ∼1100 km s⁻¹, detected toward Cepheus A HW2. The probability to detect three similar (and extremely broad) features as a result of line confusion at three different frequency ranges is also very small. We thus conclude that these features are likely associated with the emission of the H40α, H34α, and H31α RRLs, formed in the high-velocity HW2 ionized jet (Section 5).

Figure 1 (lower panels) shows a zoom-in of the continuum-subtracted RRL spectra, smoothed to a velocity resolution of 15–17 km s⁻¹. The continuum emission was subtracted by fitting a polynomial function of order one.

Although less clear for the H40α line, the extremely broad RRL profiles are asymmetric and have a similar kinematical structure with two broad (redshifted and blueshifted) velocity components. The two-component Gaussian fits of this emission are shown in Figure 1 (see solid and dashed lines). The derived parameters for the redshifted (R) and blueshifted (B) components are given in Table 1.

Table 1 also reports the contribution from only the free–free continuum emission at 3, 1.9, and 1.4 mm (Column 10), derived by extrapolating the HW2 fluxes at centimeter wavelengths and by assuming a spectral index of ∼0.6 (Rodríguez et al. 1994). These values, however, should be considered as upper limits since the actual free–free emission at millimeter wavelengths could be smaller than reported in Table 1 (Comito et al. 2007). If overestimated, these fluxes would imply an even stronger maser amplification effect for the observed RRLs (Section 4).

The derived integrated intensities of the RRLs lie above the 9σ flux level (Column 8), with σ_in the integrated intensity error in the spectra (see caption in Table 1). The derived peak and integrated intensities not only show a systematic trend to increase for increasing frequency (or decreasing quantum number n) for both velocity components, but to be brighter for the blueshifted emission compared to the redshifted component. This asymmetry in the RRL profiles can be explained as RRL maser emission in the HW2 jet (Section 5).

Ignoring the results from the H40α blueshifted component (its peak velocity and line width are factors of ∼4 and 2 larger than for H34α and H31α, Table 1), the averaged peak velocities and line widths are, respectively, −50 km s⁻¹ and 360 km s⁻¹ for the blueshifted emission, and 360 km s⁻¹ and 200 km s⁻¹ for the redshifted gas.

4. LINE-TO-CONTINUUM FLUX RATIOS: RADIO RECOMBINATION LINE MASERS IN HW2

Martín-Pintado et al. (1989) showed that the generation of RRL emission at millimeter wavelengths can suffer from non-LTE effects that lead to the formation of RRL masers in ionized winds. Since Cepheus A HW2 shows similar properties to the RRL maser object MWC349A, it is possible that the RRLs toward HW2 also form under non-LTE conditions.

In Section 3, we have shown that there is a trend for the RRL peak and integrated intensities to increase with frequency. This behavior is expected for RRL emission, since the integrated line-to-continuum flux ratios for RRLs (ILTRs, defined as δνTL/TC; Martín-Pintado et al. 1989) increase with frequency as ν₁,₁ for optically thin emission and LTE conditions. From Table 2 (Columns 2 and 3), however, we find that the measured ILTRs for these lines clearly deviate from the LTE predictions. The RRLs detected toward HW2 are therefore affected by maser effects. Like MWC349A (Column 4 in Table 2), the deviations from LTE for the ILTR of the H40α line are less prominent than those of H34α and H31α at higher frequencies. This is explained by the fact that the βₙ factors (the βₙ factor is proportional to the effective absorption coefficient of the RRL; Walmsley 1990) are expected to be more negative for RRLs with n ≤ 35 than for those with n = 40, at the electron densities of (1–5) × 10⁴ cm⁻³ derived toward HW2 (Curiel et al. 2006).

### Table 1

| RRL  | ν (MHz) | λ (mm) | TL (Jy) | ν_LSR (km s⁻¹) | Δν (km s⁻¹) | TL Δν (Jy km s⁻¹) | S₁ (Jy) | S₂ (Jy) |
|------|--------|-------|---------|----------------|------------|-------------------|--------|--------|
| H40α | 99022.96 | 3.0 | B | 0.0029 (0.0010) | −210 | 1.9 (0.1) | 0.12 | 0.059 |
|     |        |      | R | 0.0034 (0.0010) | 368 | 1.9 (0.05) | 0.12 | 0.059 |
| H34α | 160211.52 | 1.9 | B | 0.053 (0.009) | −60 | 1.4 (0.7) | 0.37 | 0.082 |
|     |        |      | R | 0.024 (0.009) | 400 | 1.4 (0.5) | 0.37 | 0.082 |
| H31α | 210501.77 | 1.4 | B | 0.055 (0.006) | −36 | 18.5 (0.4) | 0.69 | 0.099 |
|     |        |      | R | 0.035 (0.006) | 316 | 8.9 (0.4) | 0.69 | 0.099 |

Notes.

a Total continuum (dust + free–free) emission flux measured toward HW2.

b Free–free continuum flux obtained by assuming a spectral index of ∼0.6, as derived from the VLA data of Rodríguez et al. (1994).

The error in the RRL peak intensity corresponds to the 1σ noise level in the spectra (1 mJy, 9 mJy, and 6 mJy for the H40α, H34α, and H31α RRLs, respectively; see lower panels in Figure 1).

d The error in the integrated intensity flux of the RRLs is calculated as σ₁ = 1σ × √Δν × Δν, with Δν the velocity resolution of ∼15–17 km s⁻¹ in the RRL spectra (see Section 3), and Δν the line width derived in the Gaussian fit (Column 7 in this table).

e Derived from the continuum flux measured with the PdBI and SMA at 3 mm and 1.4 mm.
We try to reproduce the observed RRL profiles toward HW2 by using the three-dimensional radiative transfer model of Martín-Pintado et al. (1993, 2002, 2011), which includes the LTE departure coefficients, $b_n$ and $b_n^*$, calculated by Walmsley (1990). The model considers an isothermal ($\sim 10^4$ K) collimated, bi-conical ionized radio jet with a semi-opening angle of 18° and an inclination angle with respect to the line of sight of 52°. This inclination angle is similar to that derived by Patel et al. (2005, of 62°±10°) or Vlemmings et al. (2010, of 56°). However, the semi-opening angle (18°) is a factor of $\geq 2$ larger than that derived by Rodríguez et al. (1994, of $\sim 7$:5). The determination of this angle is subject to large uncertainties since the radiocontinuum emission of the HW2 jet is variable, and its semimajor axis is unresolved (Curiel et al. 2006). Despite the 18° semi-opening angle, our model reproduces well the radiocontinuum spectrum of HW2, smoothed to the angular resolution of 0.25″ × 0.18″ of the VLA observations of Rodríguez et al. (1994). The X- and Y-axes show the offsets (in arcseconds) with respect to the major and minor axes of the jet. Contours are the same as in Rodríguez et al. (1994), i.e., −3, 6, 9, 12, 15, 20, 30, and 50 times the r.m.s. (30 μJy) in the VLA 3.6 cm image. Beam is shown at the lower left corner. Lower panels: spectra of the H40α, H34α, and H31α lines predicted by our model assuming LTE (dashed lines) and non-LTE conditions (solid lines), overlaid on the RRL profiles measured toward HW2 (black histograms). Numbers indicate the factors by which the intensities of the predicted spectra have been multiplied in order to qualitatively compare the observations with the modeling (see Section 5).

The assumed electron density distribution in the HW2 jet varies as $r^{-2.11}$, with $r$ the distance to the central protostar extending out to 0.41 (285 AU at a distance of 700 pc; Reid et al. 2009). The electron density at the inner radius of 6.7 AU is $2.7 \times 10^8$ cm$^{-3}$, sufficient to obtain the maser effect in the RRLs.

To explain the extremely broad line widths and the lack of emission at systemic velocities, we have considered that the ionized gas in the jet is accelerated constantly to reach a terminal velocity of 500 km s$^{-1}$ (Curiel et al. 2006) at 35 AU from the protostar. The model also includes electron impact (pressure) broadening and a turbulent velocity of 60 km s$^{-1}$. However, pressure broadening is expected to be negligible for the observed RRLs (Keto et al. 2008).

Figure 2 (lower panels) shows the RRL profiles predicted under LTE (dashed lines) and non-LTE conditions (solid lines), overlaid on the observed RRLs. To match the observations, we needed to (red-)shift the predicted RRLs by 160 km s$^{-1}$ with respect to the systemic velocity of the cloud (−10 km s$^{-1}$;
Martín-Pintado et al. 2005). Water masers toward HW2 also show significant shifts in their peak velocities, associated with the dynamics of the HW2 rotating disk and wide-angle outflow (Torrelles et al. 1996, 2011). However, their velocity spans (∼40 km s⁻¹) are too small to explain the 160 km s⁻¹ shift. The morphology and kinematics of the inner regions in the jet are unknown. Asymmetries in the density, temperature, and kinematics between the red and blue lobes of the jet could give rise, due to the maser phenomenon, to large asymmetries in the RRL profiles, as expected from the larger spatial scales needed for RRL maser amplification compared to molecular masers (see below). Future modeling will explore whether these asymmetries are responsible for the 160 km s⁻¹ shift observed in the RRL.

From Figure 2, we find that the model qualitatively reproduces the two-component line profiles, with zero-intensity line widths of ∼1000 km s⁻¹, of the RRLs toward HW2. It can be seen that maser amplification (solid lines) occurs at radial velocities smaller than ±300 km s⁻¹ with respect to the systemic velocity of the jet. This is due to (1) high enough electron densities at those velocities (3 × 10⁴–4 × 10⁷ cm⁻³; Streltnitski et al. 1996) and (2) large enough coherent lengths, which lead to substantial amplification of the radiation along a velocity-coherent path (Ponomarev 1994). For larger velocities (≥±300 km s⁻¹), the electron densities are also high (3 × 10³–8 × 10⁶ cm⁻³). However, the coherence length is very small making the maser effect negligible (Ponomarev 1994). Maser amplification is maximum at radial velocities of ±140–200 km s⁻¹ with respect to the systemic velocity of the jet, because the electron densities at these velocities correspond to the optimum values for maser amplification (i.e., 6.8 × 10⁶ cm⁻³ for H40α, 1.7 × 10⁷ cm⁻³ for H34α, and 3.0 × 10⁷ cm⁻³ for H31α; Figure 8 in Streltnitski et al. 1996). Toward MWC349A, Martín-Pintado et al. (1994) also reported the detection of RRL maser emission at velocities very different from the ambient cloud velocity (±60 km s⁻¹) and predicted that they arise from ionized outflowing gas (Martín-Pintado et al. 2011).

Although the model reproduces well the intensity of the H40α line, it fails to predict the intensities of the H34α and H31α lines (note that these intensities have been multiplied in Figure 2 by factors of five and three, respectively). This problem of unmatched intensities for RRLs with n < 40 was already noted by Martín-Pintado et al. (1989) for the MWC349A RRL maser object, and could be due either to small density and temperature inhomogeneities in the stellar wind, or to uncertainties in the βα coefficients (Martín-Pintado et al. 1993). Despite the unmatched intensities, our model reproduces the asymmetry observed in the RRLs (Section 3), which can only be explained by RRL maser effects. All this suggests that the extremely broad features detected in the millimeter spectra toward Cepheus A HW2 are associated with RRL masers generated in the HW2 ionized jet.

In summary, we report the detection of the H40α, H34α, and H31α RRLs toward the high-velocity ionized jet in Cepheus A HW2. This emission shows extremely broad line profiles with zero-intensity line widths of ∼1100 km s⁻¹. The derived ILTRs significantly deviate from those in LTE, suggesting that these lines are RRL masers formed in the HW2 ionized jet with expanding velocity of 500 km s⁻¹. Together with MWC349A, the discovery of RRL masers in HW2 suggests that this mechanism could be a common feature in dense UC H ii regions (Martín-Pintado 2002).

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