Non-detection of Broad Hydrogen Radio Recombination Lines in Circinus Galaxy

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ABSTRACT

The line widths of broad line regions (BLRs) of AGNs are key parameters for understanding the central super massive black holes (SMBHs). However, due to obscuration from dusty torus, optical recombination lines from BLRs in type II AGNs can not be directly detected. Radio recombination lines (RRLs), with low extinction, can be ideal tracers to probe emission from BLRs in type II AGNs. We performed RRL observations for H$_{35}$ and H$_{36}$ toward the center of Circinus galaxy with ALMA. Narrow components of H$_{35}$ and H$_{36}$, which are thought to be mainly from star forming regions around the nuclear region, are detected. However, only upper limits are obtained for broad H$_{35}$ and H$_{36}$. Since Circinus galaxy is one of the nearest AGN, non-detection of broad RRLs in Circinus galaxy at this band tells us that it is hopeless to detect broad RRL emission in local AGNs with current facilities. Submillimetre RRLs, with flux densities that are dozens of times higher than those at the millimetre level, could be the tools to directly detect BLRs in type II AGNs with ALMA, once its backend frequency coverage has been upgraded to several times better than its current capabilities.

Key words: galaxies: active; galaxies: Seyfert

1 INTRODUCTION

Supermassive black holes (SMBHs) reside in the centres of most if not all massive galaxies, and play a key role in galaxy formation and evolution (Tremaine et al. 2002; Hopkins, Narayan, & Hernquist 2006). The SMBH mass measurement is critical for understanding the growth of SMBHs and its interplay with galaxy evolution across the cosmic time. Active galactic nuclei (AGNs) are the manifestation of active accretion onto SMBHs. A method based on the broad emission lines of AGN offers the most efficient way to measure the the black-hole masses in a large number of sample from the local universe out to the most distant quasars at z=7. Such a method employs the virial theorem of broad emission line (BEL) regions in AGN where the velocity is derived based on the line width of BELs and the location of BELs is estimated through the continuum luminosity (Kaspi et al. 2005; Peterson 2014). However, this method is applicable only to type I AGN where BELs are not obscured by dusty torus. Given the fact that type II AGN may dominate the AGN population, the above problem largely limits us from a complete understandings of many fundamental problems related to SMBH masses, e.g., what is the cosmic history of SMBH growth.

For the type II AGNs without heavy obscuration, the BELs can be detected with near-IR observations. As a result, broad By line emission has been detected in some Seyfert II galaxies (Reunanen, Kotilainen, & Prieto 2002), and gave clear evidences of the existence of BLR in type II AGN. But for the majority of type II AGNs, the extinction of BLRs at near-IR band are still too high to detect BELs. A promising solution is to measure the line width of the BELs at longer wavelengths. Proper motions and radial velocities of H$_2$O mega-maser spots can be used to deduce a high precision central mass, such as for the type II galaxy NGC 4258 (Miyoshi et al. 1995; Herrnstein et al. 1999). But because of the limitation of sensitivity, this method can not be used for a large sample of type II AGN.

Being almost free of extinction, the radio recombination lines (RRLs) of hydrogen, which have been detected in the Galac-
tic H\textsc{i} regions (Hoglund & Mezger 1965) and external galaxies (Shaver, Churchwell, & Rots 1977) for decades, could be an ideal choice for such studies. The $\alpha$ lines of RRLs (from energy level $N + 1$ to $N$) are much stronger than the lines with $\Delta N > 1$ (e.g., $\beta$, $\gamma$, $\delta$ lines), where $N$ is the principal quantum number. So the first choice should be the $\alpha$ lines. The frequencies of RRLs have a wide range from centimeter to (sub-)millimeter wavelengths, which give us many choices.

The Circinus galaxy, which is an extremely nearby Seyfert II galaxy at a distance of 4 Mpc (1$''$ ~ 20 pc) (Freeman et al. 1977), has been detected in narrow H\textsc{i} emission (Oliva et al. 1994) and broad H\textsc{i} with full width half maxima (FWHM) line width of $\sim$ 3300 km s$^{-1}$ with polarized emission (Oliva et al. 1998). Near-IR Bry observations suggested that the narrow lines are from star formation activity surrounding the Seyfert nucleus rather than the narrow line region, while the broad line is not detected due to obscuration even with Bry (Müller Sánchez et al. 2006). Thus, observations of millimeter RRLs toward the Circinus galaxy with the ALMA offers a good opportunity to directly detect emission from BEL regions of type II AGNs.

In this paper, we will describe the observations and data reduction in §2, present the main results in §3 and discussions in §4, make the brief summary in §5.

2 OBSERVATIONS AND DATA REDUCTION

The observations were taken with the ALMA 12-m array on March 04 and April 29, 2017 (project number: 2015.1.00045.S, PI: Junzhi Wang). Band 4 receivers are used to cover H35$\alpha$ ($f_{\text{rest}}$= 147.047 GHz) and H36$\alpha$ ($f_{\text{rest}}$= 153.286 GHz), in the upper side band (USB) and lower side band (LSB), respectively. Each sideband was covered with two spectral line windows (SPW) of 1.875 GHz band width each. The two SPWs have an overlap of 0.18 GHz, to ensure a frequency resolution of 2.35 GHz usable frequency coverage after removing edge channels, for both LSB and USB. The 3.5 GHz frequency coverage corresponds to $\sim$7140 km s$^{-1}$ for H35$\alpha$ and $\sim$7760 km s$^{-1}$ for H36$\alpha$, respectively. Observations were taken with three executions, with 60–70 minutes observing time each. The total on source time is about 108 minutes with 42 antennas, which gave the longest baseline of $\sim$ 640 m and shortest baseline of $\sim$ 15 m.

Ganymede and J1427-4206, J1617-5848, and J1424-6807 were adopted as the flux, bandpass, and gain calibrators, respectively. Atmospheric calibrators were performed with Ganymede, J1617-5848, and Circinus, before each scans on these calibrators and targets. We calibrate the data with standard calibration procedures with Common Astronomy Software Applications (CASA), version 4.7 (McMullin et al. 2007). The default outcome from the pipeline show slight flux offset between the overlap frequency ranges in adjacent SPWs. Observations with Ganymede as the flux calibrator do not show such an issue. Therefore, we average the ALMA-monitored fluxes of the flux calibrator $^1$ J1427-4206, observed during 25 Mar. and 23 May 2016, to be 3.02$\pm$0.07 Jy, 1.89$\pm$0.09 Jy, and 1.49$\pm$0.03 Jy, at 91.5 GHz, 233 GHz, and 343.5 GHz, respectively. Then we fit its spectral index to be $-0.536 \pm 0.018$ and implement it in self\text{`y} of pipeline. After this correction, the overlap frequency ranges between SPWs are consistent.

$^1$ https://almascience.eso.org/sc/

3 RESULTS

Spatially unresolved narrow hydrogen radio recombination lines (RRLs) H35$\alpha$ and H36$\alpha$ are detected toward the center of Circinus galaxy. The spectra presented in Figure 1 and 2 are collected from the central region of $\sim$ 3$''$ in diameter. The detected lines are marked.

Then we combine all data with concat, then image and deconvolve the data with tclean of CASA, version 6.1.2, using a natural weighting and a pixel size of 0.2$''$. It gave a restoring beam of 1.34$'' \times 1.21''$ with a position angle (PA) of $-22.0$' at the USB and 1.47$'' \times 1.31''$ with a PA of $-25.2$' at the LSB. The rms level of the data cube is about 0.22 mJy beam$^{-1}$ at a frequency resolution of 19.53 MHz, which is similar to the expected rms level based on ALMA sensitivity calculator.

Figure 1. The spectra around the rest frequencies of H35$\alpha$ in the top panel and H36$\alpha$ in bottom panel, collected from the central region of $\sim$ 3$''$ in diameter. The detected lines are marked.

The central velocity of the H36$\alpha$ narrow component is 465$\pm$10 km s$^{-1}$, with the line width (FWHM) of 236$\pm$28 km s$^{-1}$, a velocity integrated flux of 1310$\pm$123 mJy km s$^{-1}$, and a peak flux density of about 5.2 mJy, based on Gaussian fitting. On the other hand, the narrow component of H35$\alpha$ is strongly contaminated by CS 3-2, which is about 10 times stronger than that of H35$\alpha$ (see Figure 1), assuming similar flux of H36$\alpha$. The continuum emissions in both LSB and USB are close to 44.5 mJy (see Figure 1). Several other molecular lines are also detected, including HC\text{3}N 15-14 &16-15, CH\text{3}CCH 8-7, CH\text{3}CN 8-7, as well as H$_2$CO 2$_2$-1$_0$ at the rest frequency of 145.602856 GHz, which is blended with HC\text{3}N 16-15 (see Figure 1 and 2). The broad RRL components of H35$\alpha$ and H36$\alpha$ are not detected (see Figure 1). Based on the noise level and assuming the line width is similar to that of broad Hz of $\sim$ 3300 km s$^{-1}$ (Oliva et al. 1998), the 3$\sigma$ upper limit of broad RRL emissions of H35$\alpha$ and H36$\alpha$ is 3x0.46 $\times$ $\sqrt{40 \times 3300}$ = 501 mJy km s$^{-1}$. The non-detection of broad RRL emissions of H35$\alpha$ and H36$\alpha$ makes it impossible to derive the real line width of broad line region in Circinus galaxy with these two lines.

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4 DISCUSSION

4.1 The nature of the narrow component of RRL

Narrow RRLs in Circinus galaxy, H91α and H92α, had been detected using the Australia Telescope Compact Array (ATCA), with line width (FWHM) of H91α+H92α about 260 km s\(^{-1}\) centered at 449 km s\(^{-1}\), which could be explained by a collection of 50 to 10 000 H II regions with temperatures of 5000 K (Roy, Goss, & Anantharamaiah 2008). H91α+H92α emissions were mainly from the central region, except for some contribution from the northeast of center region with about 10\(^{18}\), while the beam size was 11.0\(\prime\) × 9.4\(\prime\) with PA of -76\(^\circ\) (Roy, Goss, & Anantharamaiah 2008). H36α from the central 3\(\prime\) region shown in Figure 1 has a line width of 236±28 km s\(^{-1}\) and central velocity of 465±5km s\(^{-1}\), which generally agree well with the parameters from H91α and H92α.

The properties of ionized gas have also been discussed in relation to near-IR Brγ emission, to distinguish the contribution from star formation near the center of Circinus galaxy or the narrow line region (NLR) of AGN. With Brγ and H2 1-0 S(1) observations with the SINFINI on VLT UT4 at the spatial resolution of ~0.22\(\prime\) (~4.2pc) suggested that Brγ emission within the inner 1\(\prime\) in diameter is associated with star formation rather than the narrow line region of AGN (Müller Sánchez et al. 2006).

Because the NLR in Circinus galaxy was estimated to be about 100 pc (Wada, Yonekura, & Nagao 2018), which corresponds to 5\(\prime\), and no significant narrow H36α emission is found from inner 3\(\prime\) to 5\(\prime\) region from our data, we would like to suggest that even though the contribution from AGN NLR can not be fully excluded, narrow H36α emission from the inner 3\(\prime\) (~60pc) region detected with our ALMA observation should be mainly from star formation activity.

4.2 The absence of broad RRL emission

Broad emissions of both H36α and H35α are not detected (see Figure 1). There are two possible reasons for this. One is that the line emission is too weak to be detected, while the other is that the line is too broad to be covered by the bandwidth of this observation. Because of the extremely high electron density \(n_e > 10^8\) cm\(^{-3}\) of BLRs (Peterson 2014), the pressure broadening can not be neglected, especially for the low frequency RRLs. The ratio between pressure broadening and thermal Doppler effect is 1.2\(\times\)\((n_e/10^8)^{1/2} \times (N/92)^{1/2}\) (Keto, Zhang, & Kurtz 2008), where \(n_e\) is electron density in cm\(^{-3}\) and \(N\) is the principle quantum number. So, using the thermal line width (FWHM) of ~21.6 km s\(^{-1}\) for the gas with an electron temperature of \(T_e = 10000K\), the line widths of pressure broadening are 760 km s\(^{-1}\) for \(N = 40\) at about 99 GHz and 360 km s\(^{-1}\) for \(N = 36\) at about 135 GHz, respectively, if \(n_e = 10^8\) cm\(^{-3}\). Since the FWHM of broad Hα is ~3300 km s\(^{-1}\) (Oliva et al. 1998), the pressure broadening of H36α and H35α can be neglected, even if \(n_e ~ 10^9\) cm\(^{-3}\). Thus, the non-detection of broad H36α and H35α should not be caused by the limited bandwidth that is not wide enough to cover the line.

The typical size of BLRs is from several light days to hundreds of light days for over 30 reverberation-mapped AGNs (Peterson et al. 2004; Peterson 2014). However, Circinus galaxy was not included in that sample. Based on continuum emission for a wavelength range from 8.0 to 13.0 μm with the MIDI interferometer at the VLTI, a dense and warm (T > 330 K) disk component with a radius of 0.2 pc (~240 light days; 1pc=3.2616 light years) was found (Tristram et al. 2007). BLR was thought to be surrounded by such warm dusty disk component. Thus, the size of BLR should be smaller than that of warm dusty disk. For an ionized cloud with a radius of 0.1 pc and \(n_e\) of \(10^8\) cm\(^{-3}\), the opacity of free-free at 135 GHz is about 1.9\(\times\)\(10^7\), based on the relation of \(\tau_{ν,C} = k_{ν,C}L = 9.770 \times 10^{-3}\frac{n_e^2}{\nu^2T_e^2} [17.72 + \ln \frac{T_e}{5000}] L\) (Oster 1961), where \(n_e\) is electron density in unit of cm\(^{-3}\), \(ν\) is frequency in Hz, \(T_e\) is electron temperature in K, and \(L\) is the length of line of sight in cm. Since even if the size of individual clump of BLR is \(~10^{-5}\)pc, free-free emission is still optically thick at 135 GHz if \(n_e\) is greater than \(10^8\) cm\(^{-3}\). If \(n_e\) is \(10^8\) cm\(^{-3}\), the free-free optical depths are 100 times higher than that for \(n_e\) of \(10^9\) cm\(^{-3}\).

If atomic hydrogens in BLR that emit radio recombination lines are under local thermal equilibrium (LTE) conditions, there should not be line emission when free-free emission is optically thick at the same frequency. However, the level populations of atomic hydrogens can be inverted in such ionized gas clouds (Strelinski, Ponomarev, & Smith 1996) and (Zhu et al. 2022). Based on the model in Zhu et al. (2022), the line to continuum ratio at the line peak is about 1% for H36α with FWHM of turbulence to be 3300 km s\(^{-1}\), where the continuum emission is due to free-free from electrons in BLR. Since the total continuum at 321 GHz at the nuclear region is only about 50 mJy (Hagiwara et al. 2021), which include thermal dust emission and optically thin free-free emission, the optically thick free-free emission from BLR should be less than 50 mJy at this frequency. Since optically thick free-free continuum is ~\(ν^2\), it should be less than 9 mJy at 135 GHz, while total continuum is about 44 mJy (see Figure 1). It is impossible to detect a signal weaker than 0.09 mJy, which is ~1% of the optically thick free-free emission, with our observation at the rms level of 0.46 mJy at the frequency resolution of 19.53MHz.

The flux of optically thick free-free emission at given frequency is related to electron temperature \((T_e)\) and solid angel (Ω) as \(F = T_e × Ω\). \(T_e\) can only vary within a very small range around 10000K and Ω is \(\propto (d/D)^2\), where \(d\) is the source size and \(D\) is the distance to the earth. For Circinus galaxy at the distance of 4 Mpc (17.7 ~ 20pc) (Freeman et al. 1977), if the BLR is 0.2 pc in diameter (i.e., 0.1pc in radius), the view angle is 0.01\(\prime\), which gives the conversion factor from K to Jy is \(≈ \frac{1}{1.7} \times 10^6\). Thus, the free-free continuum from BLR will be 17mJy at 135 GHz if the size is 0.1pc in radius. Since the estimated upper limit of optically thick free-free emission at 135GHz is 9 mJy, the radius of BLR in Circinus should be less than 0.07 pc.

4.3 Future prospects

With the non-detection of broad H35α and H36α in Circinus galaxy at the distance of 4 Mpc (Freeman et al. 1977), as one of the closest type II AGNs, it is hopeless to detect such emission at similar
frequency with ALMA. Since the line to continuum ratio is about 1% for H36α (see §4.2), if we expect to detect the signal with line peak of ~0.5 mJy, the optically thick free-free emission at 135 GHz should be ~50 mJy, which requires the radius to be ~0.17pc at the distance of 4 Mpc, or ~0.54pc for 40 Mpc, which is larger than the maximal size of BLR of reverberation-mapped AGNs (Peterson et al. 2004; Peterson 2014), even if the filling factors of BLRs are unity.

Sub-millimeter RRLs, which are stronger than that at millimeter band, can be another choice for sensitivity consideration. We use H26α at 353.6 GHz as an example to do such estimation. For an ionized cloud with radius of 0.1 pc, the optical depth of free-free emission at this frequency is about 2300, if $\tau = 0.019pc$ at the distance of 4 Mpc, or $\tau = 0.059 pc$ for 40 Mpc. The capability of detection will be better with the higher frequency of RRL. However, the frequency coverage of ALMA with maximal capability of ~3.7GHz can not provide enough velocity coverage to detect broad RRL emission. The corresponding velocity coverage at 353.6 GHz for H26α is only ~3140 km s$^{-1}$. Non-detection of such broad emission of H26α in the famous Seyfert II galaxy NGC 1068 had been reported in the literature (Izumi et al. 2016), which was mainly due to the limited velocity coverage at sub-millimeter wavelength.

Thus, even though it can not be done with current (sub-)millimeter facilities, observing RRLs at sub-millimeter band with ALMA after the upgrade of wide bandwidth, or at millimeter band with next generation Very Large Array (ngVLA), are possible to directly detect BLRs from local AGNs in the future.

5 SUMMARY

With ALMA observations of H35α and H36α toward Circinus galaxy, we obtained upper limit of these lines from broad line regions, which are thought to be with line widths (FWHM) of thousands of km s$^{-1}$, in type II AGNs. Narrow H36α emission with line width (FWHM) of 236±28 km s$^{-1}$ at ~10σ level, which is thought to be mainly from star forming regions around the nucleus region, is detected. Narrow H35α, contaminated by CS 3-2, is also detected.

With the estimation by free-free continuum emission and line to continuum ratio at this frequency, we conclude that broad H35α and H36α in Circinus galaxy can not be detected with ALMA due to limited sensitivity. Since Circinus galaxy is one of the nearest type II AGN, it is hopeless to detect broad H35α and H36α for other local AGNs. On the other hand, sub-millimeter RRLs, which can be dozens stronger than H36α, can be used to direct detect BLR in local AGNs with the ALMA, after its backend is upgraded to be several times better than current capability.

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DATA AVAILABILITY

The original data observed with ALMA can be accessed by ALMA archive system at http://almascience.eso.org/asax/. If anyone is interested in the calibrated data, please contact Junzhi Wang at junzhiwang@gsu.edu.cn.

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