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TEMPORAL VARIATION OF HCO^+ 1–0 GALACTIC ABSORPTION LINES TOWARD NRAO 150 AND BL LAC

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Abstract: We present observations of HCO^+ 1–0 absorption lines toward two extragalactic compact radio sources, NRAO 150 and BL Lac with the Korean VLBI Network in order to investigate their time variation over 20 years by Galactic foreground clouds. It is found that the line shape of –17 km s^{-1} component changed marginally during 1993–1998 period and has remained unaltered thereafter for NRAO 150. Its behavior is different from that of H_2CO 1_{10}–1_{11}, suggesting chemical differentiation on $\sim$ 20 AU scale, the smallest ever seen. On the other hand, BL Lac exhibits little temporal variation for the HCO^+ and H_2CO lines. Our observation also suggests that Korea VLBI Network performs reliably in the spectrum mode in that the shapes of the new HCO^+ 1–0 spectra are in good agreement with the previous ones to an accuracy of a few percent except the time varying component toward NRAO 150.

Key words: ISM: abundance — ISM: molecules — quasars: individual (NRAO 150, BL Lac) — technique: interferometric

1. INTRODUCTION

Interstellar clouds tend to be highly turbulent and inhomogeneous due to large Raynolds numbers and compressibility. Instabilities and various energy inputs of Galactic shear rotation, supernova explosion, and stellar wind, generate complicated hierarchical structures. Probing the structure of interstellar clouds down to the smallest scale may be one of the utmost concerns in the field.

For observational studies of interstellar cloud structures, one needs images with fine details and interferometers can provide them. VLBI can obtain images with angular resolutions higher than those of interferometers, but the VLBI systems currently in use can detect only very strong non-thermal radiation from, e.g., maser spots within molecular clouds. It is impossible to image general interstellar clouds in emission in thermal transitions.

Another way to explore the cloud structure is to monitor the time variations of absorption lines produced by the Galactic interstellar cloud in front of extragalactic compact radio sources. Due to the proper motion of the interstellar clouds with respect to the sight line from the earth to the compact sources, different part of the clouds will occult the compact sources over time. Using this method, Marscher et al. (1993) and Moore & Marscher (1995) compared the H_2CO 6 cm absorption lines taken in intervals of a few years to derive statistical properties of intervening clumpy molecular clouds. Liszt & Lucas (2000) presented comprehensive absorption line studies with OH and HCO^+ and suggested that the profile variation might be due to chemical inhomogeneities, instead of the density fluctuation. Araya et al. (2014) investigated the spectral variation of the 6 cm H_2CO lines toward NRAO 150 over 20 years and proposed a cylindrical filament structure intruding the line of sight.

Many investigators have continuously used this method to probe fine scale structures in various spectral range from UV to radio (Boissé et al. 2005; Rao et al. 2016; Smoker et al. 2011; Stanimirović et al. 2010).

Here we report the observation of HCO^+ 1–0 absorption line in the directions of NRAO 150 and BL Lac. Since absorption line study using HCO^+ started 1993 (Lucas & Liszt 1993) and a few studies have appeared subsequently (Lucas & Liszt 1996; Liszt & Lucas 2000), our study will enable investigation of time variation of HCO^+ line for about 20 years. Then we compare the time variations of HCO^+ 1–0 and H_2CO 1_{10}–1_{11} lines to look for any difference between the two. We summarize observations and data reduction in Section 2, present observational results in Section 3, and discuss their implications in Section 4.

2. OBSERVATION AND DATA REDUCTION

We chose two background extragalactic sources, NRAO 150 and BL Lac based on the study by Liszt & Lucas (2000). They observed several sources and suggested possible time variation for these objects in HCO^+ 1–0 (89.188518 GHz) between 1993 and 1998. These two sources are bright enough in mm wavelength to be used as calibrators. They are point-like (see below) when observed with interferometers and even with the Korea VLBI Network (KVN) that we used in this

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Table 1
Properties of observed sources

Source name	RA (J2000) h m s	Dec (J2000) ° ′ ″	L °	B °	Flux density* Jy
NRAO 150	03 59 29.74726	50 57 50.1614	+150.38	-1.60	4
BL Lac	22 02 43.29137	42 16 39.9800	+92.13	-10.40	3.5

*variable, at the time of observation of this study

work. Source positions and typical flux densities at the time of observation are listed in Table 1.

A single dish telescope can not be used for this study, since it picks up much more emissions in nearby directions. Instead, one must use either interferometer or VLBI system filtering out low spatial frequency components. We carried out observations with the KVN (Lee et al. 2014) on October 31, November 2, and November 3, 2013. The target sources, NRAO 150 and BL Lac, were observed with 1 hour long scans during 3 days in single polarization mode, and total integration time was ≈ 15 hours for each source. The continuum sources of 3C345, 3C454.3, and 4C39.25 were also observed at every scan between the different target sources. These continuum sources were used not only as a fringe-finder during the correlation processes but also as calibrators for the manual phase and bandpass calibration during data reduction. The system noise temperatures were typically from 160 K to 300 K.

The signals from all stations were sampled and filtered into 4 base band channels (BBCs), each with a bandwidth of 64 MHz, then recorded onto the Mark 5B system at a rate of 1 Gbits s^{-1}. The recorded data were processed by Distributed FX (DiFX) software correlator (Deller et al. 2007). The resultant data have 2048 spectral channels for each BBC, yielding a spectral resolution of 31.3 KHz.

We reduced the data using the Astronomical Image Processing System (AIPS) package following standard imaging procedures. First, the correlated FITS data were loaded by the AIPS task FITLD with the DIGICOR option as 1 to correct the quantization loss caused by the digital samplers. The four-level re-quantization process for the four-level quantized signals after the digital filter bank of KVN causes a loss of 8% (Iguchi et al. 2005), which cannot be corrected by AIPS. Therefore, an amplitude correction factor of 1.1 should be applied to the DiFX-correlated KVN data (Lee et al. 2015).

Next, the visibility amplitudes were calibrated with the system noise temperatures and antenna gains, and then bandpass characteristics were calibrated with the scans of the calibrators with the highest signal to noise ratios. The scans with the system noise temperature above 500 K were flagged out before further calibration. Manual fringe fitting was performed to remove the residual instrumental phase offsets using the calibrators, and then phase self-calibration was applied to the target sources to remove the residual fringe rate and delay. All these processes were carried out using the AIPS tasks FRING and CALIB.

Given the calibrated visibilities, we performed Fourier transformations of the visibilities to extract the intensity profiles from the image cube. Uniform weighting was applied in this image synthesis, and the synthesized beams are 1.24×0.79 milli-arcseconds^2 and 1.26×0.76 milli-arcseconds^2, and the image rms noises are 4.06×10^{-2} Jy beam^{-1} and 4.23×10^{-2} Jy beam^{-1} for NRAO 150 and BL Lac, respectively. The two sources are indeed found to be point-like in these images. There may be extended features due to jets overfilling the synthetic beam, but their contribution to total flux density will not be significant. Flux densities can be derived either from the calibrated visibilities or from the integration of the images over solid angle for point-like objects. In our observation, noises are slightly better for the calibrated mean visibilities before imaging than that derived from the images. Thus we primarily use the averaged visibilities for further analysis.

The continuum flux densities are found to be 1.2 and 2.5 Jy for NRAO 150 and BL Lac, respectively. The typical flux density of NRAO 150 is ∼ 4 Jy according to the F-GAMMA survey around the time of our observation. Thus the measured flux density of NRAO 150 is significantly low. BL Lac is also weak since another KVN observation in the continuum mode conducted at a similar epoch when we made observation, suggests its flux density of ∼ 3.5 Jy (Lee et al. 2016). The reason for the low brightness was not identified, which does not affect the subsequent analysis since we deal with spectra normalized to unity in the continuum.

The data with an original spectral resolution of 31.3 KHz was smoothed and sampled in 78.0 KHz or 0.262 km s^{-1} resolution to match the previous observations by Liszt & Lucas (2000). The profiles were divided by continuum level. Noise level of 2013 data is $\sigma(l/c) = 0.020$ for NRAO 150, while it is $\sigma(l/c) = 0.015$ for BL Lac. It was 0.018 and 0.007 in 1993 and 1998, respectively for NRAO 150, whereas it was 0.028 and 0.016 in 1993 and 1998, respectively for BL Lac (Liszt & Lucas 2000; Lucas & Liszt 1996).

3. RESULTS

The NRAO 150 spectrum taken by KVN in 2013 is displayed in Figure 1 together with that taken by Liszt & Lucas (2000) in 1998. We come across five molecular clouds with different radial velocities along the line of sight toward NRAO 150. Though Liszt & Lucas (2000) observed with PdBI, a short baseline interferometer, one can compare the spectra without correction, since the sources are resolved neither with KVN nor with

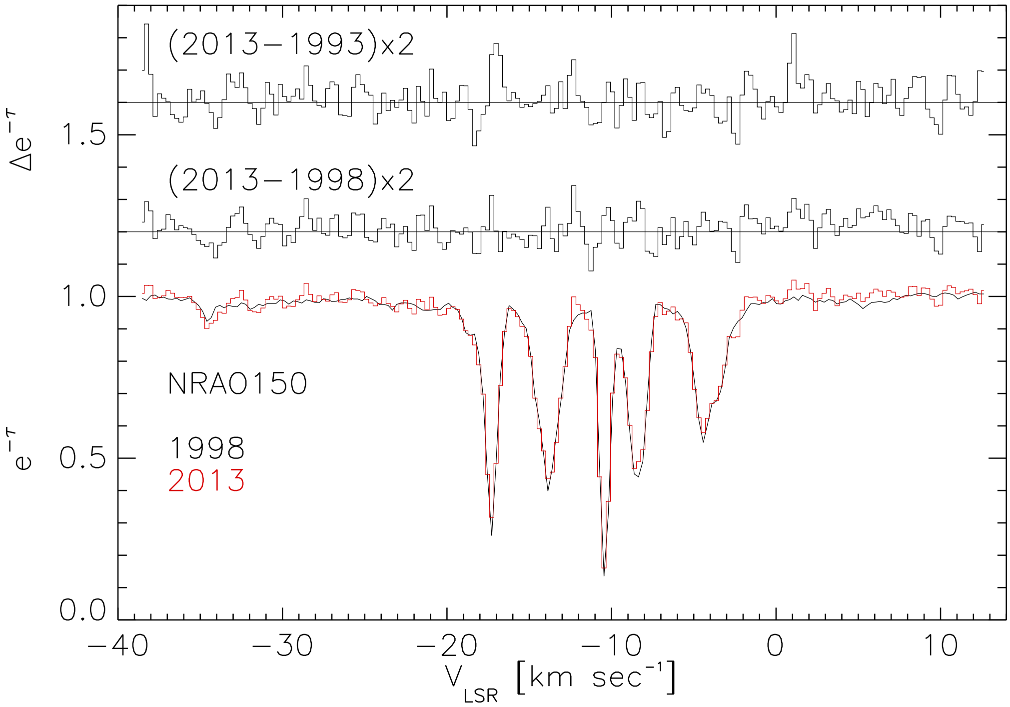

Figure 1. Spectra of HCO$^+$ 1–0 of NRAO 150 and their difference spectra

PdBI. Their spectra are in good agreement each other, despite the flux depression mentioned in Section 2.

If the profile is normalized to one in the continuum as shown in Figure 1, the scale of the ordinate is $e^{-\tau_\nu}$, where τ_ν is an optical depth of intervening molecular cloud. This can be derived from the familiar solution of radiative transfer equation for a uniform medium,

$$I_\nu = S_\nu(1 - e^{-\tau_\nu}) + B_\nu e^{-\tau_\nu}, \quad (1)$$

where S_ν is the source function of molecular cloud between observer and background continuum source and B_ν is the brightness of the background source. Since $I_\nu = B_\nu$ for line free region,

$$I_\nu / B_\nu = e^{-\tau_\nu}, \quad (2)$$

for $B_\nu \gg S_\nu$. Therefore, the normalized line profile measures the optical depth of the intervening cloud, independent of its source function. The peak optical depth of the leftmost velocity component is 1.3 and this is translated to the HCO$^+$ column density of 1.2×10^{12} cm $^{-2}$. Here the excitation temperature of HCO$^+$ 1–0 transition is assumed to be 2.7 K, because its emission spectrum is extremely weak when observed with a single dish telescope (Liszt & Lucas 2000). Other velocity components have the same order of HCO$^+$ column densities.

To discern any differences among line profiles, we present difference spectra between 2013 and 1998 and between 2013 and 1993 (Liszt & Lucas 2000) in Figure 1. Noise level of 2013–1998 spectra is $\sigma = 0.022$, and that of 2013–1993 is $\sigma = 0.029$. We particularly focus on any features near $V_{LSR} \approx -17$ km $^{-1}$ where Liszt & Lucas (2000) suggested a variation of spectra between 1993 and 1998. We do not find significant change between 1998 and 2013. On the other hand, when one compares 2013 and 1993 spectra, the –17 km s^{-1} component seems to exhibit marginal change. The difference at –17 km s^{-1}, 0.091, is larger than three sigma of the difference spectra. Similar to the fake feature at +1 km s^{-1} in the line free region, this may not be real. However, the largest profile variation occurs in the line shoulder which is most sensitive to any change of radial velocity or column density and three consecutive channels are prominent over noise level. Thus we cautiously conclude that the –17 km s^{-1} component has changed marginally from 1993 to 1998 and has remained unaltered since then. For this period, the optical depth changes from 0.93 to 0.73 or $\Delta\tau \approx 0.20$ according to Equation (2).

The BL Lac spectrum taken by KVN and the difference spectra are displayed in Figure 2 with the same legends as those of NRAO 150. Noises of the difference spectra are $\sigma = 0.021$ for 2013–1998 and $\sigma = 0.028$ for 2013–1993, respectively. The peak optical depth is 1.5 and the HCO$^+$ column density is estimated to be 2.4×10^{12} cm^{-2}. In deriving the column density we assumed the excitation temperature of 2.7 K, for the same reason as that of NRAO 150. BL Lac seems to have changed little from 1993 to 2013. Though Liszt & Lucas (2000) mentioned possible change in the central

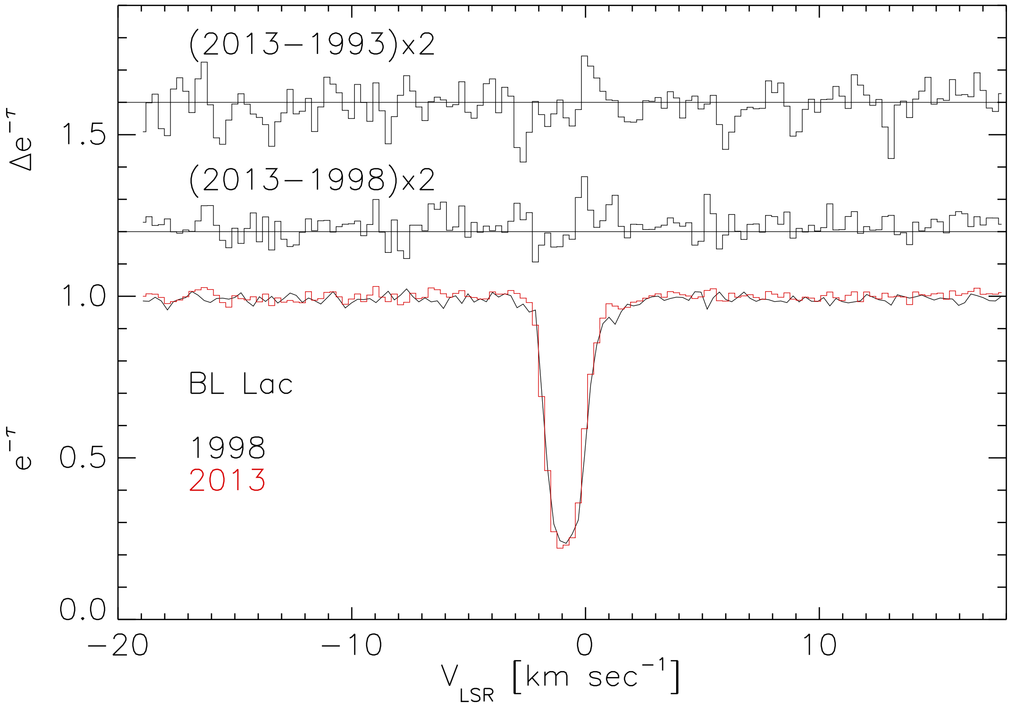

Figure 2. Spectra of HCO^+ 1–0 of BL Lac and their difference spectra

part of the absorption between 1993 and 1998, it is unlikely. It seems that BL Lac absorption lines have been stable for 20 years.

4. DISCUSSIONS

4.1. Temporal Variation

Araya et al. (2014) analyzed VLA observations in H_2CO $1_{10} - 1_{11}$ 6 cm transition since 1990 for NRAO 150. Except for a very weak and broad component at –8.6 km s^{-1}, there are two velocity components at –17 and –10 km s^{-1} that appear also in HCO^+. Their Figures 3 and 6 show that the –10 km s^{-1} component has been gradually increasing in strength from 1990 to 2009, while the –17 km s^{-1} component has remained unchanged. The increase in absorption strength amounts to 8% for the –10 km s^{-1} component for 20 years. The stronger absorption of H_2CO is contrasted with the changeless HCO^+ line for the –10 km s^{-1} velocity component. On the other hand, for the –17 km s^{-1} velocity component, the H_2CO line was not changing, while the HCO^+ line absorption was slightly decreasing from 1993 to 1998.

Araya et al. (2014) suggested a cylinder-like structure intruding the line of sight or, with less emphasis, an equivalent abundance gradient, in order to explain the increasing absorption of the –10 km s^{-1} cloud toward NRAO 150. However it is evident that none of them are compatible with the changeless spectra of HCO^+. In the case of the –17 km s^{-1} cloud, the cloud thickness and/or the abundance of the HCO^+ changed, while those of H_2CO had been kept constant for the 1993–1998 period. Since the cloud geometry will be common to both molecules, the most likely and simple explanation reconciling both HCO^+ and H_2CO observations is that the two molecules distribute differently. Actually Liszt & Lucas (2000) suggested that the temporal change of HCO^+ could be attributed to abundance variation over a distance that the molecular cloud traversed during the time intervals of 1993 to 1998, which corresponds to $\sim$ 20 AU (see below). Small dense clumps in diffuse medium suggested by Moore & Marscher (1995) is ruled out at least for NRAO 150, since HCO^+ is not observed in emission when observed with a single dish telescope (Liszt & Lucas 2000). Our observation further suggests that the spatial distributions are different from molecule to molecule. This chemical differentiation is not new on larger scales (e.g., Nagy et al. 2015). The virtue of our observation lies on the manifestation of the chemical differentiation on much smaller scales.

In order to know how small scale we are witnessing, we need to translate the time intervals to physical lengths that a sight line has traversed. The translation involves the motions of Earth and Sun that are fully known, but also depends on the intrinsic motion of the molecular clouds added to the Galactic rotation that we do not know. According to Araya et al. (2014), this ranges from 0 to 5 AU per year for a peculiar motion of 10 km s^{-1} depending on the direction of motion. Then the time interval of five years corresponds to $0 - 25$ AU. Thus our observation indicates the chemical differentiation on $\sim$ 20 AU scale, which may be the smallest scale ever seen for Galactic molecular clouds.

If these objects were observed in more transitions of the molecules under study, one would comprehensively understand the variations of physical quantities including temperature, density, and abundance over the small length scale, which may be feasible with ALMA (Ando et al. 2016).

Araya et al. (2014) also presented H_2CO absorption lines for BL Lac from 1990 to 2009. The lines do not seem to change for this period, which is consistent with those of HCO$^+$. It seems that there are few small scale structures in Galactic molecular clouds toward BL Lac.

4.2. Reliability of KVN in Spectrum Mode

Intensity calibration of KVN for continuum sources was seriously discussed in Lee et al. (2015). They verified that specific intensities and flux densities obtained with KVN were in good agreement to those of VLBA with reasonable corrections at the stages of cross correlation and data reduction. Since the cross correlation does not distinguish continuum and line sources and the data reduction flow is the same for both continuum and line objects in AIPS except for its final stages, one may think that spectra obtained with KVN are as reliable as the flux density of continuum sources. But this needs to be eventually proved.

Our observation unintentionally did that job since it was found that the shapes of the spectra obtained with KVN for NRAO 150 and BL Lac coincide with those obtained with different instruments at different epochs to an accuracy better than a few percents. Of course the time varying component is excluded from this comparison. This verification was made possible due to the fact that the sources were point-like and the transition was thermal. The flux density from our observation which are significantly low for unknown reasons, may make the assertion less credible. However it is quite evident that the coincidence in spectral shape can not be due to chance. The reproducibility of spectral line shape together with the reasonable amplitude calibration (Lee et al. 2015) suggests that the KVN works dependably for line sources.

5. SUMMARY

We conducted the observation of thermal HCO$^+$ 1–0 absorption line formed by foreground molecular clouds toward compact quasars, NRAO 150 and BL Lac to find any temporal change during 20 years, which might provide us with clues to the fine scale inhomogeneity of molecular clouds. It is found that only the –17 km s^{-1} component of HCO$^+$ 1–0 line toward NRAO 150 marginally changed during 1993 to 1998 and has remained unchanged after that period. Other velocity components show little change since 1993. On the other hand, for H_2CO 1_{10}–1_{11}, the –10 km s^{-1} component has changed for 20 years, while the other component has been unaltered (Araya et al. 2014). Cylindrical structure moving across the line of sight proposed by Araya et al. (2014) can not explain these observations together. The most likely explanation will be that abundance distribution is different from molecule to molecule. This may be the first identification of chemical differentiation on $\sim$ 20 AU scale. There has been no or little change both in HCO$^+$ 1–0 and H_2CO 1_{10}–1_{11} spectra of BL Lac for the 20 years. Coincidence in shape among HCO$^+$ spectra taken at different epochs with different instruments except the time-varying –17 km s^{-1} component of NRAO 150, combined with the fidelity in amplitude calibration (Lee et al. 2015), suggests that KVN system performs reliably for line sources as well as continuum objects.

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