Discovery of Extraplanar H I Clouds and a H I Tail in the M101 Galaxy Group with FAST

Jin-Long Xu1,2, Chuan-Peng Zhang1,2, Naiping Yu1,2, Ming Zhu1,2, Peng Jiang1,2, Jie Wang1, Xin Guan1,2, Xiao-Lan Liu1,2, and Xiaolian Liang1,3

1 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China; xujl@bao.ac.cn
2 CAS Key Laboratory of FAST, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, People’s Republic of China
3 University of Chinese Academy of Sciences, Beijing 100049, People’s Republic of China

Received 2021 June 27; revised 2021 September 13; accepted 2021 September 13; published 2021 November 19

Abstract
We present a new high-sensitivity H I observation toward nearby spiral galaxy M101 and its adjacent 2° × 2° region using the Five-hundred-meter Aperture Spherical radio Telescope (FAST). From the observation, we detect a more extended and asymmetric H I disk around M101. While the H I velocity field within the M101’s optical disk region is regular, indicating that the relatively strong disturbance occurs in its outer disk. Moreover, we identify three new H I clouds located on the southern edge of the M101’s H I disk. The masses of the three H I clouds are 1.3 × 10^5 M_☉, 2.4 × 10^5 M_☉, and 2.0 × 10^5 M_☉, respectively. The H I clouds similar to dwarf companion NGC 5477 rotate with the H I disk of M101. Unlike NGC 5477, they have no optical counterparts. Furthermore, we detect a new H I tail in the extended H I disk of M101. The H I tail detected gives reliable evidence for M101 interaction with the dwarf companion NGC 5474. We argue that the extraplanar gas (three H I clouds) and the H I tail detected in the M101’s disk may originate from a minor interaction with NGC 5474.

Unified Astronomy Thesaurus concepts: Extragalactic astronomy (506)

1. Introduction
Galaxies show an almost constant star formation rate throughout the Hubble time (Panter et al. 2007), such as the Milky Way. In order to maintain stable star formation and prevent gas from exhaustion, these galaxies need a continuous supply of fresh gas. Theoretical arguments predict that galaxies prevent gas from exhaustion, these galaxies need a continuous supply of fresh gas. Theoretical arguments predict that galaxies

2. Observation and Data Processing
2.1. Observation
To show the H I (1420.4058 MHz) gas distribution surrounding M101, we mapped a 2° × 2° region centered at position of R.A. = 14:03:12.6 and decl. = 54:08:34.4 using the Five-hundred-meter Aperture Spherical radio Telescope (FAST), during 2021 January and April. FAST is located in Guizhou, China. The aperture of the telescope is 500 m, and its effective aperture is about 300 m. The 19-beam array receiver system in dual polarization mode is used as the frontend. It formally works in the frequency range from 1050 MHz to 1450 MHz. For spectral-line observation, FAST is equipped with two digital backend systems, Spec(F) and Spec(W–N). We select Spec(F) backend, which has a bandwidth of 500 MHz and 1,048,576 channels, resulting a frequency resolution of 476 Hz and corresponding to a velocity resolution 0.1 km s⁻¹ at 1.4 GHz.

Mapping observation uses the multibeam on-the-fly (OTF) mode. This mode is proposed to map the sky with 19 beams simultaneously, and has a similar scanning trajectory. The half-power beam width (HPBW) is about 2°/9 at 1.4 GHz for each
beam. The pointing accuracy of the telescope was better than 8°. To satisfy Nyquist sampling, the parameter of rotation angle is available in this mode. If the scan is along the latitude lines, the receiver platform needs to turn 23°4. While along the longitude lines, it needs to turn 53°4. After turning the angle, an interval between two adjacent parallel scans is about 1°14. Besides, we set the scan velocity of 15° s⁻¹ and an integration time of 1 s per spectrum. During observations, system temperature was around 25 K. For intensity calibration, noise signals with amplitude of 10 K were injected under a period of 2 s. A total of 67 minutes is needed to acquire a 2° × 2° map. In order to improve sensitivity, we observed two times for M101 with the multibeam OTF mode. Jiang et al. (2019, 2020) gave more details of the FAST instrument.

2.2. Data Reduction

For each spectrum with a bandwidth of 500 MHz, we intercept 2.2 MHz data for processing, which can cover the whole velocity range of M101. The data reduction was performed with the PYTHON package and the GILDAS package. First of all, we will calibrate the unit of the spectrum into kelvin for each polarization signal through the following transformation:

\[ T_A = T_{\text{cal}} - \frac{P_{\text{off}}}{P_{\text{on}} - P_{\text{off}}}, \]

where \( T_A \) is calibrated antenna temperature, while \( T_{\text{cal}} \) is noise diode temperature. \( P_{\text{on}} \) and \( P_{\text{off}} \) are power values when the noise diode is on and off, respectively. The correction for the line intensity to brightness temperature \( (T_B) \) was made using the formula \( T_B = T_A / \eta_{\text{sm}} \). Here \( \eta_{\text{sn}} \) is the main beam efficiency, which can be determined by \( \eta_{\text{sn}}(\lambda) = 0.8899(\theta_{\text{sm}}/(\lambda D))^2 \eta_0 \) (Downes 1989), where \( \theta_{\text{sm}} \) is the beam width in radians, \( D \) is the effective aperture, \( \lambda \) is the observing wavelength, and \( \eta_0 \) is the aperture efficiency. The \( \theta_{\text{sn}} \) and \( \eta_0 \) values for each beam can be derived from Jiang et al. (2020). Here we only give the main beam efficiency of the central beam (Beam 1); \( \eta_{\text{sm}} \) is ~0.75 at 1.4 GHz.

Using the ArPLS algorithm, we mitigate radio frequency interference (RFI) by a fitting procedure of the data in the time–frequency domain. After combining the two polarizations, a first-order polynomial was used to fit baseline structure and subtract continuum sources to a line-free range of each spectrum. The L-band 19-beam receiver of FAST has a low frequency baseline structure and side-lobe correction. Once the spectra have been fully calibrated, we apply them to a grid in the image plane. Each grid is adopted as 1°/5. This grid can be made in a TAN projection projection in the World Coordinate System as described by Calabretta & Greisen (2002).

Finally, we make the calibrated data into the standard fits-cube format. For further processing of fits-cube data, we use the GILDAS package, such as for channel merging and regridding with a pixel of 1°/5 × 1°/5. The velocity resolution is smoothed to 2.1 km s⁻¹, then the noise rms is about 56 mK (2.6 mJy beam⁻¹) for the M101 region. To facilitate comparison with the previous observations of M101 by the HI4PI data (Collaboration et al. 2016), the FAST cube data are smoothed and resampled to the same angular resolution and pixel scale with the HI4PI data. Figure 1 shows comparison of the H I spectrum of NGC 5474 in the M101 galaxy group from the FAST map (black line) and HI4PI map (red line). Both spectra are integrated over the NGC 5474 region. It is clear that the two spectra agree within the noise.

3. Results

Figure 2 shows a H I column-density contours in blue and black colors, overlaid on the DSS B-band optical image of the M101 galaxy group. The blue contour is 7.3 × 10¹⁵ cm⁻² (5σ). The black contours begin at 5.6 × 10¹⁵ cm⁻² in steps of 1.3 × 10¹⁵ cm⁻². The integrated-velocity range is from 105 km s⁻¹ to 395 km s⁻¹. The beam of FAST is shown in the bottom left corner. Both spectra are integrated over all of the NGC 5474 region. It is clear that the two spectra agree within the noise.
Figure 3. Velocity field obtained from the H I data cube (the first moment map), which is shown in both contours and color scale. The velocity contours go from 120 to 380 km s$^{-1}$ in steps of 8 km s$^{-1}$. The red dashed circles and ellipse represent the three newly identified H I clouds. Letters C1, C2, and C3 illustrate the locations of the three H I clouds. The black pluses mark the center positions of M101 and members. The NGC 5477 region and $R_{25}$ (8') of the M101's optical disk are shown in two black dashed circles, respectively.

Figure 2, we see that the H I disk around the spiral galaxy M101 much more extends than the bright optical counterpart. The outskirts of the H I disk are asymmetric, and extend toward the southwest. It has been as also seen in previous single-dish observations and array synthesis observations. However, compared with the previous array synthesis observations (van der Hulst & Sancisi 1988; Walter et al. 2008), our new observations show a more extended structure around M101. The extra extended region is roughly considered as that between the blue contour and the first black contour in Figure 2. While compared with the early single-dish observations (Huchtmeier & Witzel 1979; Mihos et al. 2012), we find that the extended structure has a tail toward the south. In addition, a dwarf companion NGC 5477 and a massive giant H II region NGC 5471 reside near the northeast of the extended disk. The other companion NGC 5474 is located at the south of the extended disk, whose H I disk also displays an extended structure toward the northwest. In a H I column-density map, Huchtmeier & Witzel (1979) detected a diffuse-gas bridge connecting M101 with NGC 5474, yet our highly sensitive observation with a relatively high angular resolution do not detect the bridge between the two galaxies, as shown in Figure 2.

Figure 3 shows the H I velocity field of the M101 galaxy group. The isophotal size ($R_{25}$) of the M101's optical disk is 8' (Mihos et al. 2013). As seen in Figure 3, the H I velocity field of M101 within the optical disk region is regular and looks unperturbed. Outside the optical disk region, the velocity field becomes irregular. While the velocity field of NGC 5477 shows an irregular velocity gradient, and whose recessing velocity is very close to that of the perturbed northeast region of the H I disk (Combes 1991), indicating that the velocity field of NGC 5477 has been combined with that of M101. Furthermore, the H I velocity field of NGC 5474 is symmetric, and shows an S-like shape. Rownd et al. (1994) indicated that the gas disk of NGC 5474 has a pronounced warp developing beyond the optical disk. The most exciting thing is that we identify three new H I clouds located on the southern edge of M101's H I disk. The three identified H I clouds have no optical counterparts. To further analysis and discussion, we name them at C1, C2, and C3, respectively. In particular, the C2, whose velocity fields are very similar to that of the companion NGC 5477.

In order to explore the dynamic relationship of the companions and H I clouds with M101, we made position–velocity (PV) diagrams along different directions, which are shown in Figure 4. From these PV diagrams, we first identify four high-velocity H I clouds, as indicated by red arrows in panels (a), (d), and (e). Here the gas leaving from the H I disk is considered a high-velocity cloud (HVC). The positions of the four HVCs are marked in four red pluses in the top left panel of Figure 4. From the top left panel, we see that the four HVCs are mainly located outside the optical disk region. One of the HVCs in panel (e) of Figure 4 is indicated by G1. By comparing with the previously detected HVCs in M101, we find that the remaining three HVCs are associated with those detected by van der Hulst & Sancisi (1988). In panels (c)–(e), we also see that the newly detected H I clouds C1, C2, and C3 similar to NGC 5477 in panel (f) rotate with the H I gas disk of M101. Additionally, compared with the identified HVCs, C1, C2, and C3 have low relative velocity, and their sizes are larger than those of the HVCs, suggesting that these detected clouds may be intermediate velocity cloud (IVC). Furthermore, at an intensity of 3 mJy beam$^{-1}$ ($\sim\sigma$), Mihos et al. (2012) detected a weak H I gas bridge connecting M101 with NGC 5474 from their PV diagram. However, in panel (b) of Figure 4, we do not identify the connecting bridge with nearly the same sensitivity.

4. Discussion and Conclusions

4.1. New H I Clouds Detected around M101

Compared with the previous H I observations toward the M101 galaxy group (Huchtmeier & Witzel 1979; Walter et al. 2008; van der Hulst & Sancisi 1988), we detected a more extended H I disk around M101 using FAST with a high-sensitivity H I observation. On the southern edge of the extended H I disk, we identify three new H I clouds (C1, C2, and C3). The velocity field of the H I cloud C2 very similar to the dwarf companion NGC 5477 shows an irregular velocity gradient. From the PV diagrams in panels (c)–(e) of Figure 4, we also see that the H I clouds C1, C2, and C3 similar to NGC 5477 rotate with the H I gas disk of M101. Unlike the companion NGC 5477, however, they have no optical counterparts. This situation is also very similar to nearby galaxy NGC 2403. In the NGC 2403, a newly detected cloud rotates with the main H I disk, see Figure 6 of de Blok et al. (2014).

From the observation of Green Bank Telescope (GBT), Mihos et al. (2012) also found two new H I clouds on the southwest of M101’s H I disk. To distinguish the previously identified H I clouds, we made channel maps overlaid on the DSS B-band optical image, see Figure 5. From panel (a) of Figure 5, we see that except for the H I gas associated with the main disk, there are two H I clouds located on the southwest, indicated by two black arrows. By comparing with velocity range and position, the two H I clouds in panel (a) should be those identified by Mihos et al. (2012). Hence, here the H I clouds C1, C2, and C3 in panels (b) and (c) of Figure 5 are identified for the first time from M101’s H I disk.
The total mass of the three HI clouds in M101 can be calculated by \( M = 2.72mD^2 \int N(x, y) dx dy \), where the factor 2.72 is the mean atomic weight, \( m \) is the mass of atomic hydrogen, \( D \) is the adopted distance to the clouds, \( dx \) and \( dy \) are the pixel sizes. The column density \( N(x, y) \) in each pixel can be estimated as \( N(x, y) = 1.82 \times 10^{18} \int T_B dv \), where \( T_B \) is the line brightness temperature, and \( dv \) is the channel width. We adopt the distance (6.9 Mpc) of M101 as those of the three HI clouds, yielding that the masses of C1, C2, and C3 are \( 1.3 \times 10^7 M_\odot \), \( 2.4 \times 10^7 M_\odot \), and \( 2.0 \times 10^7 M_\odot \), respectively. The obtained masses are a lower limit because we can only identify cloud emission when they are not projected against the main disk. Meanwhile, we also estimated that the sizes of C1, C2, and C3 are about 18 kpc, 19 kpc, and 15 kpc, respectively. From Figure 5, we see that the HI clouds C1 and C3 have connected in projection with the main disk, while the HI cloud C2 seem not to overlap with the main disk in panel (c). These extraplanar gases in M101 are similar to the filaments found in NGC 891 (Oosterloo et al. 2007), NGC 2403 (Fraternali et al. 2002; de Blok et al. 2014), and M33 (Sancisi et al. 2008). Sancisi et al. (2008) suggested that such extraplanar gases are the most remarkable ones found in the halo regions of these galaxies because they may be direct evidence of cold gas accretion from outside.

### 4.2. The Origin of the Extraplanar Gas in M101

For the origin of the extraplanar gas, it seems to have two mechanisms (Sancisi et al. 2008), fountain-driven accretion and accretion from intergalactic space. In fountain-driven accretion, the hot gas rises into the halo, condenses into cold clouds, and returns to the disk. Here the extraplanar gas may be driven by star formation. Figure 6 shows the far-ultraviolet (FUV) emission image of M101 overlaid with the HI column-density contours. The FUV data, obtained from Dale et al. (2009), are used to trace emission from hot stars (de Blok et al. 2014).
Figure 5. Channel maps (blue and black contours) overlaid on the DSS B-band optical image. The channel separation and width are about 4 km s$^{-1}$. The velocity ranges are shown in the top left corner of each panel. (a) The two arrows mark two HI clouds identified by Mihos et al. (2012). The blue contours begin at 0.33 K km s$^{-1}$ in steps of 0.20 K km s$^{-1}$, and in steps of 2.27 K km s$^{-1}$ for the denser region indicated by black contours. (b) The blue contours begin at 0.50 K km s$^{-1}$ in steps of 0.67 K km s$^{-1}$, and in steps of 13.36 K km s$^{-1}$ for the denser region indicated by black contours. (c) The blue contours begin at 0.50 K km s$^{-1}$ in steps of 0.67 K km s$^{-1}$, and in steps of 13.36 K km s$^{-1}$ for the denser region (black contours). The dashed circles and ellipse represent the three newly identified HI clouds. The beam size of FAST is indicated in the bottom left corner of each panel.

Figure 6. HI column-density contours in blue black colors, overlaid on the FUV emission image of M101. The contour levels are the same as those in Figure 2. The blue dashed circles and ellipse represent the three newly identified HI clouds.

However, from Figures 2 and 6, we did not see evidence of violent star formation in the projection directions of these clouds and the HVC G1 identified by us. Thus, the fountain-driven accretion cannot cause these IVC HI clouds and the HVC G1 detected in M101.

While for the other mechanism, the extraplanar gas is either directly accreting from the intergalactic medium or is the result of a minor interaction with a neighboring dwarf galaxy, as in the case in NGC 2403 (de Blok et al. 2014). According to Dekel & Birnboim (2006) and Mihos et al. (2013), if massive galaxies at low redshift undergo a cold flow accretion, they will host a massive hot halo. While the hot gas traced by the X-ray emission in M101 is diffuse and only correlated with the spiral arms (Kuntz et al. 2003). Furthermore, as shown in Figure 6, the FUV emission in M101 is also similar to the X-ray emission. Thus, M101 does not host a massive hot halo, or even a warm halo, arguing that the massive galaxy M101 ($M_{\text{tot}} \approx 10^{12} M_\odot$; Huchtmeier & Witzel 1979) would not be experiencing any significant cold flow accretion from the intergalactic medium currently (Mihos et al. 2013). Simultaneously, it also means that the main galaxy M101 may not have enough energy to eject such massive clouds found by us and Mihos et al. (2012). Hence, the extraplanar gas in M101 may be the result of a minor interaction with a neighboring dwarf galaxy, but there is still a lack of reliable evidence for the interaction.

From Figure 3, we see that the HI velocity field within the optical disk region of M101 is regular, indicating that the relatively strong disturbance occurs in the outer disk. While the asymmetric outer disk of M101 has also been believed to arise from an interaction with a companion (Beale & Davies 1969; Rownd et al. 1994; Waller et al. 1997; Mihos et al. 2013, 2018). The two closest companions to M101 are NGC 5477 and NGC 5474. NGC 5474 has a low luminosity ($M_V = -15.3$). Mihos et al. (2012) suggested that it cannot be massive enough to create such a strong morphological response in a giant Sc spiral like M101. For the other companion NGC 5474, it is more luminous than NGC 5477. Huchtmeier & Witzel (1979) and Mihos et al. (2012) detected some diffuse HI gas between M101 and NGC 5474 in a HI column-density map and a PV diagram, respectively, strengthening the case for a recent interaction between the two galaxies.

While our high-sensitivity HI observation with a relatively high resolution (2′/9) did not detect the diffuse HI bridge connecting M101 with NGC 5474 in a HI column-density map (see Figure 2) in a PV diagram (see panel (b) of Figure 4). From Figure 2, we find that the distance between M101 and NGC 5474 is about 15′. While the angular resolutions of the previous observations from Huchtmeier & Witzel (1979) and Mihos et al. (2012) are about 9′, which is nearly close to the distance between the two galaxies. Hence, the above two observations may not be able to distinguish the gas between them well. We suggest that the previously detected bridge between the two galaxies is likely due to beam dilution created by the role of low spatial resolution. Generally, galaxy–galaxy interaction can give rise to star formation in tidal debris, while Garner et al. (2021) did not detect an abundance of star formation between M101 and NGC 5474, also suggesting that...
the gas between the two galaxies is very weak or there is no gas like bridge. We did not detect a H I bridge between the two galaxies, but we identified a slightly extended H I disk for NGC 5474. It means that the two galaxies have undergone only a weak interaction, just like the work of Garner et al. (2021).

In addition, as shown in Figure 2, we detected a new H I tail on the southern edge of the extended H I disk of M101. Generally, the H I tail indicates an ongoing minor merger and the recent arrival of external gas, and then can be considered as direct evidence of cold gas accretion (Sancisi et al. 2008). Compared with the positions of the H I tail, the newly detected H I clouds seem to represent other H I tails. Here the H I tails detected in M101 gives reliable evidence for M101 interaction with NGC 5474. Thus, we conclude that the extraplanar gas (three H I clouds) and the H I tail detected in the M101 disk are likely to origin from a minor interaction with the companion NGC 5474. Furthermore, because FAST has high sensitivity and relatively high angular resolution, it can detect and separate the relatively weak and small gas structures around galaxies. This will play an important role in the study of galaxy evolution.

We thank the referee for insightful comments that improved the clarity of this manuscript. We acknowledge the support of the National Key R&D Program of China No. 2018YFE0202900. This work was also supported by the Youth Innovation Promotion Association of CAS, the National Natural Science Foundation of China (grant No. 11933011), and supported by the Open Project Program of the Key Laboratory of FAST, NAOC, Chinese Academy of Sciences.

ORCID iDs

Xiao-Lan Liu © https://orcid.org/0000-0002-1768-9591
Xiaolian Liang © https://orcid.org/0000-0002-7384-0014

References

Beale, J. S., & Davies, R. D. 1969, Natur, 221, 531
Calabretta, M. R., & Greisen, E. W. 2002, A&A, 395, 1077
Collaboration, H., Ben Bekhti, N., Flöer, L., et al. 2016, A&A, 594, A116
Combes, F. 1991, A&A, 243, 109
de Blok, W. J. G., Keating, K. M., Pisano, D. J., et al. 2014, A&A, 569, A68
Dale, D. A., Cohen, S. A., Johnson, L. C., et al. 2009, ApJ, 703, 517
Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2
Downes, D. 1989, in in Lecture Notes in Physics, Vol. 333, Evolution of Galaxies; Astronomical Observations, ed. I. Appenzeller, H. J. Habing, & P. Lena (Berlin: Springer), 351
Fraternali, F., van Moorsel, G., Sancisi, R., & Oosterloo, T. 2002, AJ, 123, 312
Garner, R., Mihos, J. C., Harding, P., & Watkins, A. E. 2021, ApJ, 915, 57
Han, J. L., Wang, C., Wang, P. F., et al. 2021, RAA, 21, 107
Huchtmeier, W. K., & Witzel, A. 1979, A&A, 74, 138
Jiang, P., Tang, N.-Y., Hou, L.-G., et al. 2020, RAA, 20, 064
Jiang, P., Yue, Y. L., Gan, H. Q., et al. 2019, SCPMA, 62, 959502
Kornreich, D. A., Haynes, M. P., & Lovelace, R. V. E. 1998, AJ, 116, 2154
Kuntz, K. D., Snowden, S. L., Pence, W. D., & Mukai, K. 2003, ApJ, 588, 264
Larson, R. B. 1972, Natur, 236, 21
Matheson, T., Joyce, R. R., Allen, L. E., et al. 2012, ApJ, 754, 19
Mihos, J. C., Durrell, P. R., Feldmeier, J. J., Harding, P., & Watkins, A. E. 2018, ApJ, 862, 99
Mihos, J. C., Harding, P., Spengler, C. E., Rudick, C. S., & Feldmeier, J. J. 2013, ApJ, 762, 82
Mihos, J. C., Keating, K. M., Holley-Bockelmann, K., Pisano, D. J., & Kassim, N. M. 2012, ApJ, 761, 186
Oosterloo, T., Fraternali, F., & Sancisi, R. 2007, AJ, 134, 1019
Pezzulli, G., & Fraternali, F. 2016, MNRAS, 455, 2308
Panter, B., Jimenez, P., Heavens, A. F., & Charlot, S. 2007, MNRAS, 378, 1550
Rownd, B. K., Dickey, J. M., & Helou, G. 1994, AJ, 108, 1638
Sancisi, R., Fraternali, F., Oosterloo, T., & van der Hulst, T. 2008, A&AR, 15, 189
Sommer-Larsen, J. 2006, ApJ, 644, L1
Waller, W. H., Bohlin, R. C., Cornett, R. H., et al. 1997, ApJ, 481, 169
Walter, F., Brinks, E., de Blok, W. J. G., et al. 2008, AJ, 136, 2563
van der Hulst, J. M., & Sancisi, R. 1988, AJ, 95, 5