Atomic hydrogen (H I) is the least bound component of galaxies and is therefore the easiest (and hence first) to be stripped off and spread around during interactions. Thus, the distribution of the very diffuse H I and its velocity field can provide new information about the earliest interactions. To study the diffuse H I associated with Stephan’s Quintet (SQ), we carried out deep mapping observations of the 21 cm H I emission over a region of around 30′ × 30′ centred on SQ (Fig. 1) using the 19-beam receiver of Five-hundred-meter Aperture Spherical Telescope (FAST). The FAST observations and data reduction are described in the Methods. As shown illustratively in Fig. 2, the final data cube includes 304 spectra in Δν = 20 km s⁻¹ channels covering the velocity range of 4,600–7,600 km s⁻¹, with an average root-mean-square (r.m.s.) noise of 0.16 mJy per beam and an average beam size of 2.9′. The mapping satisfies the Nyquist sampling criterion with beams separated by 1.4′ in the right ascension direction and 1.2′ in the declination direction. The original data cube has a H I column-density sensitivity of 1σ = 1.2 × 10¹⁷ cm⁻² per channel, which is improved to 1σ = 4.2 × 10¹⁶ cm⁻² per channel when smoothed to 4′. Results of the analysis of the whole data cube will be presented elsewhere. In this Article we report only the discovery of a large H I structure in the velocity range of 6,550–7,650 km s⁻¹.

Figure 3a presents the integrated H I emission map in the velocity range of 6,550–7,650 km s⁻¹ overlaid on the deep MegaCam optical colour image. The map has an angular resolution of 4.0′ and Δν = 200 km s⁻¹ (ten times the channel width) with an H I column-density error of 1σ = 1.34 × 10¹⁷ cm⁻². The base contour starts from N_HI = 7.4 × 10¹⁷ cm⁻² (at a 5σ level). The map shows a large H I structure of around 0.6 Mpc in size, which has two parts: an extended source centred on SQ and a diffuse feature attached to the south edge of the source. The extended source encompasses the previously detected 6,600 km s⁻¹ H I component associated with the debris field. As shown by the cyan contours in Fig. 3a, the high-resolution (beam = 19.4′ × 18.6′) Very Large Array (VLA) observations detected only the highest-density stephan's quintet.
part of the 6,600 km s⁻¹ component ($N_{\text{H}} = 5.8 \times 10^{19}$ cm⁻²), which is confined to the central region ($D = 0.1$ Mpc) of the extended source. Most of the high-density H i gas traces the optically detected inner and outer tails plus a compact cloud (north-west of NGC 7319), which may be responsible for the formation of the inner and outer tails, respectively. NGC 7318b is a 'new intruder', which is currently colliding into the intragroup medium of SQ and triggering a large scale shock. NGC 7320 is a foreground galaxy. The small red circles mark the central positions of the FAST 19-beam receiver in these pointings, and the characters P1, P2, ..., P16 inside the circles identify the different pointings. The large magenta circles ($D = 2.9'$, that is, the half-power beam size) show the coverage of the 19 beams in the first pointing (see Methods for more details).
Two new detections of unresolved sources can also be found in Fig. 3a. NGC 7320a, detected with the signal-to-noise ratio $S/N = 36$, has an H I mass of $M_{\text{HI}} = (6.3 \pm 0.2) \times 10^8 M_\odot$ and a $v_{\text{HI}} = 6,702 \pm 24$ km s$^{-1}$. The other source Anon 7, a 4.40 detection, has an H I velocity of $6,654 \pm 16$ km s$^{-1}$ and an H I mass of $(2.2 \pm 0.5) \times 10^8 M_\odot$. More discussions about these two sources are given in the Methods.

We examine in Fig. 4 the individual spectra in box A and box B to investigate the physical nature of the diffuse feature. No diffuse stellar radiation is detected in these regions down to the limit of the deep MegaCam image. Spectra of beams with detections of $S/N > 4$ are marked by pink boxes and those with $3 < S/N \leq 4$ by green boxes. Galaxies brighter than the r-band magnitude $r = 20$ mag found in the SDSS photometric redshift (photo-z) catalogue are also marked in Fig. 4. Only two of them have photo-z < 0.1 (marked by red circles) and the remaining 28 have photo-z $\geq 0.1$ (orange circles). Given the error of the photo-z ($\delta z/(1 + z) = 0.02$) and the redshift of SQ ($z = 0.02$), galaxies with photo-z $\geq 0.1$ are very unlikely to be at the same redshift of SQ (probability < 0.001). We can rule out with high confidence the possibility of the diffuse feature being associated with a collection of gas-rich galaxies (even including those fainter than $r = 20$ mag), because it needs at least four such galaxies to cover all beams with significant detections of $S/N > 4$ (one for those in the upper-left corner of box A, two for those in the right half of box A and one for that in box B) and the probability that they happen to have about the same radial velocity is extremely low.

H I clouds without stellar counterparts have been found in and around many galaxy groups/clusters. Most of them, as the authors of ref. have argued, can be explained by tidal debris of galaxy interaction involving very extended H I disks instead of 'dark' or 'almost dark' galaxies. Given its location and velocity, the diffuse feature is most likely to be related to the debris field. A hypothetical scenario for the formation of the diffuse feature is that NGC 7320a ($v = 6,702$ km s$^{-1}$ and currently around 300 kpc away from the SQ centre) passed through the SQ centre approximately 1.5 Gyr ago (assuming a relative transverse velocity of 200 km s$^{-1}$) and pulled out from one of the core member galaxies of SQ a tidal tail, which developed into the diffuse feature we see now. Another possibility is that, like the large Leo Ring ($D = 0.25$ Mpc) the diffuse feature could be the product of a high-speed head-on collision between another old intruder and one of the core members of SQ. In this scenario, the collision triggers an expanding density wave that pushes gas in an extended H I disk of the target galaxy outwards to form a very large ring, of which the diffuse feature is the high-density part. A candidate for such an intruder could be Anon 4 ($v = 6,057$ km s$^{-1}$, $M_{\text{HI}} = 1.1 \times 10^8 M_\odot$).
The integrated H\textsc{i} emission in the velocity range of 6,550–6,750 \text{ km s}^{-1}.\n
(a) Contour map of the integrated H\textsc{i} emission in the velocity range of 6,550–6,750 \text{ km s}^{-1} overlaid on the composite colour image (u, g, r) of the deep CFHT MegaCam observation. The red circle at the bottom right illustrates the angular resolution (half-power beam size $= 4.0''$) of the FAST map after smoothing. The contours start from $N_{\text{HI}} = 7.4 \times 10^{17} \text{ cm}^{-2}$ (at 5.5σ level) with an increment of a factor of 2. The red lines delineate the boundary of the FAST observations. The cyan contours in the centre are adopted from the VLA observations for the 6,600 \text{ km s}^{-1} component of SQ, with angular resolution of 19.4'' $\times$ 18.6''. They have the base level at $N_{\text{HI}} = 5.8 \times 10^{18} \text{ cm}^{-2}$ and the increment of a factor of 2. The area occupied by the newly discovered diffuse feature is filled with a hatch pattern consisting of thin yellow dotted lines. The two green boxes marked by characters A and B cover the diffuse feature. (b) False colour map of the velocity field of the H\textsc{i} emission in the velocity range of 6,550–6,750 \text{ km s}^{-1} overlaid by the same contour map shown in (a). The units of the x and y axes are in pixels (pixel size: 1.4'' $\times$ 1.2''), and the colour of every pixel represents the flux-density weighted mean velocity whose scale is given in the scale bar on the right. (c) The H\textsc{i} spectrum of the diffuse feature. The red line is the summation of all spectra inside box A and the blue line the summation of those inside box B. The black line is the sum of the two spectra of boxes A and B.

which spatially coincides with optical galaxy LEDA 141041 (B band magnitude $B = 18.4$ mag). It has a relative radial velocity of around 600 \text{ km s}^{-1} and a projected distance of approximately 0.2 Mpc from the SQ centre. If the relative transverse velocity is around 200 \text{ km s}^{-1}, it would have taken approximately 1 Gyr for Anon 4 to move to the current position after the collision. Both scenarios proposed above suggest a formation time of the diffuse feature of more than 1 Gyr ago. They are both based on analogies to cases studied in simulations in the literature, which demonstrate that diffuse H\textsc{i} features without a stellar component can be produced in galaxy–galaxy interactions. However, two questions remain to be answered: (1) Can the tidal feature in either of the scenarios survive the subsequent interactions that triggered the formation of the inner and outer tails of SQ about (3–8) $\times$ 10$^8$ years ago? (2) Can H\textsc{i} structures with column density as low as $N_{\text{HI}} \lesssim 10^{18} \text{ cm}^{-2}$ exist on timescales of around 1 Gyr? These questions can only be answered by more sophisticated models that are built upon the existing simulations for the formation and evolution of SQ. It has been argued that cold gas of $N_{\text{HI}} \lesssim 2 \times 10^{17} \text{ cm}^{-2}$ cannot stay neutral in the intergalactic ultraviolet background radiation for more than 500 Myr (refs. 21,22). A plausible solution for this problem is the physical mechanism involving the transition between ionized and neutral phases due to thermal instabilities in the low-density gas. New simulations, which are beyond the scope of this Article, shall explore this mechanism.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-05206-x.
Fig. 4 | Individual spectra in the diffuse feature region. Individual spectra in box A and box B in Fig. 3a are overlaid on the inverted greyscale map of the CFHT MegaCam r-band image. The centre of each spectrum coincides with the pointing position of the FAST beam with which it was obtained. All spectra are plotted with the same velocity range of $[6,200, 7,200] \text{ km s}^{-1}$ and flux-density range of $[-0.5, 1.5] \text{ mJy per beam}$. The short vertical red line on the top of every spectrum marks the position of $v = 6,642 \text{ km s}^{-1}$ (the flux-density-weighted mean velocity of the diffuse feature). The spectra with detections of $S/N > 4$ are identified by pink boxes and those with detections of $3 < S/N \leq 4$ by green boxes. Galaxies brighter than $r = 20 \text{ mag}$ are marked by red circles if they have $\text{photo-z} < 0.1$ or orange circles if they have $\text{photo-z} \geq 0.1$. The large red circle in the upper-left corner (outside the boxes) illustrates the half-power beam size of the FAST observations.
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Methods

FAST observations

The deep H\textsc{i} mapping observations were carried out in September and October of 2021 using the FAST 19-beam receiver in the standard ON–OFF mode with the total observation time of 22.4 h including overheads (Extended Data Table 1). The FAST 19-beam L-band Array is currently the largest multibeam feed array for H\textsc{i} observations in the world. Details about its properties and performance can be found in ref. 32. The 19 beams are arranged in a hexagonal configuration with the neighbouring beams separated by 5.7'. The observations have a central frequency of 1,391.64 MHz and a frequency coverage of 1,050–1,450 MHz with a resolution of 7.63 kHz (\(\Delta v = 1.65 \text{ km s}^{-1}\)). For the 19 beams, the average half-power beam-width at 1,391 MHz is 2.9' (Extended Data Table 2). To meet the Nyquist sampling criterion and fill the gaps between beams in the focal plane, we carried out 16 pointings in a 4 \times 4 rectangular grid in the north-up orientation (Fig. 1). The final mapping covers a region of around 30' \times 30' centred on S\O with 304 sky pixels (beam positions in the sky), and the separation between the nearest pixels is 1.4' in the right ascension direction and 1.2' in the declination direction. The 1σ pointing error of individual beams is 7.9' (ref. 32). At each pointing, six cycles of ON–OFF integrations were conducted, with the OFF position at 40' southeast from the ON position. Each ON or OFF took 300 s integration with a sampling frequency of 1 Hz. The total on-target time for each pixel was 1,800 s (Extended Data Table 1). To minimize the effects of standing waves and sidelobes, all observations were confined within the zenith angle of 20°.

Compared with the scan-mapping mode, which is more suitable for large sky surveys such as the FAST Extragalactic HI Survey32, our observational strategy provides an alternative for deep and small maps (\(\leq 30'\)), which can take advantage of the ON–OFF mode in more accurately removing various systematic effects such as the standing waves and baseline wobbling.

Data reduction and calibration

For each sky pixel observed by a given beam, we reduced the spectral data following a similar procedure to that presented in ref. 33. The spectra of the two polarizations were reduced separately (and eventually combined after the consistency check). The data were grouped in ON–OFF cycles. Each ON (or OFF) has 300 samplings which were averaged and calibrated (that is, converted from digital counts to Kelvin), resulting in a single raw spectrum. During the observations, a calibration signal of 10 K was injected for a duration of 20 s at the beginning of every ON–OFF cycle, and these data were used to calibrate the antenna temperature, \(T_{\text{a}}\). The calibration error is on the order of 10%. Repeating this, we obtained a raw spectrum for every ON or OFF. As examples, the upper panel of Extended Data Fig. 1 presents the individual raw ON–OFF spectra obtained by the M01 beam during the first pointing observation (the P1 pixel in Fig. 1). The mean of these spectra is presented in the middle panel of Extended Data Fig. 1. It is affected significantly by the standing waves, which can be well fitted by a sine function locally. The spectrum has been converted from \(T_{\text{a}}\) (in K) to flux density (in mJy). The gain factor that converts \(T_{\text{a}}\) to flux density (in the units of K Jy\(^{-1}\)) depends on the frequency and varies from beam to beam. The values for individual beams at 1,391 MHz, derived by interpolating values at other frequencies adopted from ref. 33, are presented in Extended Data Table 2. The next step was to remove the standing waves together with the baseline from the spectrum. The bottom panel of Extended Data Fig. 1 presents the final spectrum at sky pixel P1 after the subtraction of a baseline modelled by a sinusoidal (representing the standing waves) plus a polynomial (for the baseline gradient). We converted the frequency to velocity by adopting the optical redshift convention and the local standard of rest reference frame and rebinned the spectrum into bins of \(\Delta v = 20 \text{ km s}^{-1}\). The above process was carried out repeatedly for every sky pixel observed in our observations.

It is worth noting that, if the standing waves and baseline vary significantly during a given observation, it is better to carry out the removal of the standing waves and baseline for spectra of individual ON–OFFs instead of doing it for their mean. However, in a test in which we did the standing waves and baseline subtraction for each ON–OFF and then used the median of the baseline-subtracted spectra of ON–OFFs as the final spectrum at a given pixel, we got a noisier product. It seems that the wavelength of the standing waves (in the frequency domain) in a given observation is rather constant (although the phase changes from cycle to cycle). Consequently, the effect of the standing waves in the mean of the spectra of individual ON–OFFs is still a well-defined sinusoidal with the same wavelength, which can be easily removed. Hence, because the mean spectrum is less noisy than individual spectra and therefore a more accurate model for the standing waves and the baseline can be obtained, subtracting the baseline model from the mean spectrum can achieve a better result.

The final data cube was constructed from the 304 individual spectra obtained using this technique, with a velocity coverage of 4,600–7,600 \text{ km s}^{-1} in 20 \text{ km s}^{-1} bins. A uniform half-power beam-width of 2.9' was adopted for all spectra, neglecting the small variation of the beam size among different beams.

The actual half-power beam-width of individual beams at 1,391 MHz, derived from interpolations of values adopted from ref. 2, are listed in Extended Data Table 2. The units of the flux density of the spectra in the cube are mJy per beam. To find the flux density in units of mJy for a given spectrum, a factor of \(A = (B/2.9')^2\) should be multiplied to the value taken from the cube, where \(B\) is the half-power beam-width (in arcmin) of the beam with which the spectrum was observed.

In the 16-pointing observations, each of the 19 beams covered 16 adjacent sky pixels. The mean and the standard deviation of the measured r.m.s. noise of these 16 spectra are also listed in Extended Data Table 2. The r.m.s. noise of each spectrum was measured in the two velocity intervals of 4,700–5,000 \text{ km s}^{-1} and 7,000–7,500 \text{ km s}^{-1}, where no H\textsc{i} signal was detected. Beam M16 stands out as the noisiest beam in the array, with a mean r.m.s. of 0.26 mJy per beam and a standard deviation of 0.14 mJy beam. The false colour map of the r.m.s. noise in the left panel of Extended Data Fig. 2 shows that indeed pixels in the top-right corner that were covered by beam M16 have higher noise than others. The histogram of the distribution of the r.m.s. noise at all sky pixels is shown in the right panel of Extended Data Fig. 2. The mean of the r.m.s. is 0.16 mJy per beam with a standard deviation of 0.05 mJy per beam. It is worth noting that strong radio frequency interference (RFI) in the frequency range of our observations was a serious issue in the early stages of this project. The operation team of FAST did excellent work in discovering and removing the source of the RFI in a relatively short time. All of our observations were carried out after the removal of the RFI source. Consequently, our observations were not affected by any significant RFI.

Smoothing

The H\textsc{i} data cube obtained above is highly redundant in the sense that a sky area of the size of a single beam (\(D = 2.9'\)) is covered by multiple beams (beam separation \(1.4' \times 1.2'\)). When making channel maps and integrated emission maps from the data cube, applying a Gaussian-kernel convolution (that is, smoothing) makes good use of this redundancy. This minimizes the noise due to the signal fluctuations in adjacent beams and results in significant improvement in the H\textsc{i} column-density sensitivity. The only disadvantage is a slight degradation in the angular resolution. For single-channel maps, the mean r.m.s. of 0.16 mJy per beam corresponds to a H\textsc{i} column-density sensitivity of \(10 = 1.2 \times 10^{15} \text{ cm}^{-2}\) per channel (\(\Delta v = 20 \text{ km s}^{-1}\)). When a Gaussian kernel of full-width at half-maximum (FWHM) = 2.8' is applied, the H\textsc{i} column-density sensitivity is improved by a factor of 2.9 to \(10 = 4.2 \times 10^{16} \text{ cm}^{-2}\) per channel whereas the angular resolution is degraded only slightly (by a factor 1.4) to 4.0'. The improvement in
the H I column-density sensitivity is particularly important for the exploration of diffuse extended emission. In Extended Data Fig. 3 we present the contour map of the integrated H I emission in the velocity range of $6.550 - 6.750$ km s$^{-1}$ before the smoothing. Compared with the map after the smoothing (Fig. 3a), the low H I column-density features in Extended Data Fig. 3 are more fragmented mainly because of the signal fluctuations in adjacent beams. On a linear scale the pre- and after-smoothing resolutions are 72.5 kpc and 100 kpc, respectively, which is not a significant difference given that we are searching for extended diffuse H I gas on a linear scale of a few 100 kpc.

Sidelobe correction

The data cube is corrected for the sidelobes using the images of individual beams of the 19-beam receiver, which provide information about the point spread functions of the beams. For each beam, a 'sidelobe responsivity function' is defined by the difference between the point spread function and the 'main beam', the latter being approximated by a two-dimensional Gaussian with the FWHM equal to the half-power beam-width. In the calculation of the sidelobe corrections, we consider only the effects due to the central extended source associated with the SQ group. The FAST observations also detected numerous other H I sources in the SQ neighbourhood in the velocity range of $5,500 - 7,000$ km s$^{-1}$. They are much fainter than the central SQ source and therefore their contributions to the sidelobes are neglected.

The first step is to estimate the sidelobe contribution to the map of integrated H I emission in the velocity range of $6,550 - 6,750$ km s$^{-1}$, which encompasses the peak of the H I spectrum of SQ2. The original integrated H I emission map (the observed map) is first deconvolved with the main beam of M01 (the central beam of the 19-beam receiver). Then all pixels outside a circular aperture of $D = 10.6'$, within which the central extended source is located, are masked. The result is then taken as our approximation for the 'truth map'. The sidelobe contribution to any given pixel in the observed map is estimated by the following equation:

$$F_{\text{sid}}(x_i, y_i) = \sum_{m=1}^{M} \sum_{n=1}^{N} T(x_i, y_i) \times R_k(x_i - x_m, y_i - y_m),$$

where $x_i$ and $y_i$ are the coordinates of the pixel centre, $T(x_i, y_i)$ is the flux in the truth map in the pixel at $x_i$ and $y_i$, $R_k$ is the sidelobe responsivity function of the beam that is pointed at the pixel $(x_i, y_i)$, and $\sum_m$ and $\sum_n$ are summations along the $x$ and $y$ directions, respectively. Extended Data Figure 4 presents the map of the sidelobe contribution estimated using this method overlaid by contours of the map of integrated H I emission in the velocity range of $6,550 - 6,750$ km s$^{-1}$ (without the sidelobe correction), smoothed by a Gaussian kernel of FWHM = 2.8'. It shows that the sidelobes contribute significantly at the edge of the debris field but have a minimal effect on the diffuse feature in the south.

Neglecting the frequency dependencies of the shapes of both the sidelobes and the central SQ source, we estimate the sidelobe contribution to each channel in the data cube by scaling the map in Extended Data Fig. 4 with a factor of $C_k = S_k/S_{6,550-6,750}$, where $S_k$ (in mJy) is the flux density of SQ in the given channel and $S_{6,550-6,750}$ (in mJy km s$^{-1}$) is the integrated flux of SQ in the velocity range of $6,550 - 6,750$ km s$^{-1}$. Finally, we obtain the sidelobe corrected data cube by subtracting the estimated sidelobe contribution from every channel map in the cube. The 304 spectra in the resulting data cube are presented illustratively in Fig. 2.

Detections of two new H I sources in the SQ neighbourhood

In the velocity range of $6,550 - 6,750$ km s$^{-1}$ we detected two new unresolved H I sources in the SQ neighbourhood (Extended Data Table 3). Their H I spectra are presented in Extended Data Fig. 5. The spectrum of the source associated with NGC 7320a shows a typical double-horn profile consistent with the highly edge-on optical morphology of the galaxy. To confirm the association of the H I source and the optical galaxy, we made a long-slit optical spectroscopic observation (1 h exposure) for NGC 7320a on the night of 21 December 2021 using the 2.4 m telescope at Lijiang Observatory. The optical spectrum is presented in Extended Data Fig. 6. The radial velocity obtained from the optical spectrum is $6,729 \pm 59$ km s$^{-1}$, which is consistent with the H I velocity ($6,702 \pm 24$ km s$^{-1}$). The other source is a 4.4σ detection without obvious optical counterpart and therefore we name it Anon 7 following the convention in the literature.

Data availability

Observational data are available from the FAST archive (http://fast.bao.ac.cn) 1 year after data collection, following FAST data policy. The data that support the findings of this study are openly available in Science Data Bank at https://www.scibd.cn/s/jiflee.

Code availability

The Python and IDL code for the data reduction pipeline is available at https://www.scibd.cn.s/jiflee.

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Author contributions

C.K.X. carried out the observations, performed the data reduction, calibration and modelling, and interpreted the results. C.C. carried out the data reduction, calibration and modelling, interpreted the results and collected ancillary data. P.N.A. interpreted the results and proofread the manuscript. P.-A.D. and M.Y. interpreted the results and collected ancillary data. N.-Y.T. carried out the observations and calibration. Y.G., Y.S.D., J.-S.H., U.L. and F.R. interpreted the results.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Fig. 1 | Examples of intermediate products of spectral data reduction. **Upper Panel:** Individual ON-OFF spectra obtained by beam M01 in Pointing 1 observation (i.e. the data obtained at the pixel P1 in Figure 1). An offset of 0.2 K is added to every spectrum relative to the previous one in order to make them separated from each other. **Middle Panel:** The mean of the ON-OFF spectra in the upper panel. The units of the flux density are converted from K to mJy using the gain factor taken from Extended Data Table 2. The red line shows the baseline model derived by fitting the parts of the spectrum free of signals (marked by orange color) using a sinusoidal (representing standing waves) plus a polynomial (for baseline gradient). **Bottom Panel:** The spectrum after the baseline removal. The frequency is converted to radial velocity in the optical convention relative to the local standard rest reference frame (LSR). The orange line presents the rebinned spectrum with the velocity bin-width of 20 km s$^{-1}$. 
Extended Data Fig. 2 | Spectral R.M.S. noise of individual sky pixels. **Left:** The false color image of the r.m.s. noise at different sky pixels. **Right:** Histogram of the distribution of the r.m.s. noise.
Extended Data Fig. 3 | The HI emission in the velocity range of 6550–6750 km s$^{-1}$ (unsmoothed). Contour map of integrated HI emission (unsmoothed) in the velocity range of 6550–6750 km s$^{-1}$ overlaid on the composite color image (u, g, r) of the deep CFHT MegaCam observation. The red circle at bottom-right illustrates the angular resolution (FWHM = 2.9') of the FAST map (unsmoothed). The cyan contours in the center are adopted from the VLA observations for the 6600 component of SQ$^0$, with angular resolution of 19.4' × 18.6'. They have the base level at $N_{\text{HI}} = 5.8 \times 10^{19}$ cm$^{-2}$ and the increment of a factor of 2. The red lines delineate the boundary of the FAST observations. The same Box A and Box B that mark the location of the diffuse feature in Figure 3a are plotted here to facilitate the comparison between the two figures.
Extended Data Fig. 4 | Sidelobe contribution to the integrated HI emission in the velocity range of 6550–6750 km s⁻¹. False color image of the sidelobe contribution overlaid by the contour map of integrated HI emission in the velocity range of 6550–6750 km s⁻¹ (before the sidelobe correction and after the convolution by a Gaussian kernel of FWHM = 2.8'). The contours start from 20 mJy km s⁻¹ beam⁻¹ (corresponding to $N_{\text{HI}} = 7.4 \times 10^{17}$ cm⁻² for the original beam of FWHM = 2.9') with an increment of a factor of 2.
Extended Data Fig. 5 | HI spectra of NGC 7320a and Anon 7. HI spectra of two newly detected HI sources (NGC 7320a and Anon 7) in the SQ neighborhood.
Extended Data Fig. 6 | Optical spectrum of NGC 7320a. Optical spectrum of NGC 7320a obtained at Lijiang 2.4 meter telescope. The vertical dotted lines mark the positions of corresponding emission/absorption lines redshifted according to the best-fit redshift $z = 0.02243 \ (v = 6729 \text{ km s}^{-1})$. 
### Extended Data Table 1 | FAST Observations

| Obs.         | date       | $t_{\text{total}}^a$ (secs) | R.A. $^b$ (2000J) | Decl. $^b$ (2000J) | cent freq. (MHz) | ON-OFF cycles | $t_{\text{on}}^c$ (secs) |
|--------------|------------|-------------------------------|-------------------|-------------------|------------------|---------------|------------------------|
| Pointing 1   | 2021-09-09 | 5580                          | 22:35:43.37       | +33:59:20.6       | 1391.64          | 6             | 1800                   |
| Pointing 2   | 2021-09-14 | 5580                          | 22:35:50.39       | +33:59:20.6       | 1391.64          | 6             | 1800                   |
| Pointing 3   | 2021-09-11 | 5580                          | 22:35:57.31       | +33:59:20.6       | 1391.64          | 6             | 1800                   |
| Pointing 4   | 2021-09-13 | 5580                          | 22:36:04.23       | +33:59:20.6       | 1391.64          | 6             | 1800                   |
| Pointing 5   | 2021-09-15 | 4860                          | 22:35:43.37       | +33:58:06.1       | 1391.64          | 6             | 1800                   |
| Pointing 6   | 2021-09-18 | 4860                          | 22:35:50.39       | +33:58:06.1       | 1391.64          | 6             | 1800                   |
| Pointing 7   | 2021-09-20 | 4860                          | 22:35:57.31       | +33:58:06.1       | 1391.64          | 6             | 1800                   |
| Pointing 8   | 2021-09-24 | 4860                          | 22:36:04.23       | +33:58:06.1       | 1391.64          | 6             | 1800                   |
| Pointing 9   | 2021-09-26 | 4860                          | 22:35:43.37       | +33:56:51.5       | 1391.64          | 6             | 1800                   |
| Pointing 10  | 2021-09-27 | 4860                          | 22:35:50.39       | +33:56:51.5       | 1391.64          | 6             | 1800                   |
| Pointing 11  | 2021-09-29 | 4860                          | 22:35:57.31       | +33:56:51.5       | 1391.64          | 6             | 1800                   |
| Pointing 12  | 2021-09-28 | 4860                          | 22:36:04.23       | +33:56:51.5       | 1391.64          | 6             | 1800                   |
| Pointing 13  | 2021-09-30 | 4860                          | 22:35:43.37       | +33:55:36.9       | 1391.64          | 6             | 1800                   |
| Pointing 14  | 2021-10-03 | 4860                          | 22:35:50.39       | +33:55:36.9       | 1391.64          | 6             | 1800                   |
| Pointing 15  | 2021-10-01 | 4860                          | 22:35:57.31       | +33:55:36.9       | 1391.64          | 6             | 1800                   |
| Pointing 16  | 2021-10-05 | 4860                          | 22:36:04.23       | +33:55:36.9       | 1391.64          | 6             | 1800                   |

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**a.** Total observation time including all overheads.

**b.** Coordinates of the pointing position of the central beam M01.

**c.** Total on-target time.

**d.** These earlier observations have higher overheads than the later observations.
## Extended Data Table 2 | Properties of beams in the 19-beam receiver

| Beam ID | Half-power size $^a$ [arcmin] | Gain factor $^b$ (Jy/K) | rms $^c$ (mJy beam$^{-1}$) | δ rms $^d$ (mJy beam$^{-1}$) |
|---------|-------------------------------|-------------------------|-----------------------------|-------------------------------|
| M01     | 2.8335                        | 16.0128                 | 0.18                        | 0.07                          |
| M02     | 2.8635                        | 15.0520                 | 0.14                        | 0.03                          |
| M03     | 2.8535                        | 15.5324                 | 0.13                        | 0.02                          |
| M04     | 2.8780                        | 15.2122                 | 0.16                        | 0.04                          |
| M05     | 2.8480                        | 15.6638                 | 0.15                        | 0.04                          |
| M06     | 2.9680                        | 15.0520                 | 0.16                        | 0.04                          |
| M07     | 2.8690                        | 14.9207                 | 0.16                        | 0.04                          |
| M08     | 2.9090                        | 14.3089                 | 0.17                        | 0.03                          |
| M09     | 2.8935                        | 14.3089                 | 0.16                        | 0.04                          |
| M10     | 2.9590                        | 15.2409                 | 0.14                        | 0.03                          |
| M11     | 2.9290                        | 14.6004                 | 0.14                        | 0.03                          |
| M12     | 2.9590                        | 14.2802                 | 0.15                        | 0.03                          |
| M13     | 2.9190                        | 15.2409                 | 0.14                        | 0.03                          |
| M14     | 2.9635                        | 14.6004                 | 0.14                        | 0.03                          |
| M15     | 2.8990                        | 13.9599                 | 0.16                        | 0.02                          |
| M16     | 2.9790                        | 13.3194                 | 0.26                        | 0.14                          |
| M17     | 2.9290                        | 13.8285                 | 0.17                        | 0.05                          |
| M18     | 2.9545                        | 13.7710                 | 0.17                        | 0.04                          |
| M19     | 2.9190                        | 14.2802                 | 0.15                        | 0.03                          |

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$^a$: Half-power beam size at 1391 MHz.
$^b$: Gain factor at 1391 MHz.
$^c$: Mean r.m.s. of the 16 spectra (bin-width of 20 km s$^{-1}$) obtained with the beam.
$^d$: Standard deviation of the r.m.s.
| Source ID | R.A. (2000J) | Decl. (2000J) | $V_{HI}$ (km s$^{-1}$) | $\Delta v_{20}$ (km s$^{-1}$) | $M_{HI}$ (10$^{8}$ M$_{\odot}$) |
|-----------|--------------|---------------|------------------------|-------------------------------|-------------------------------|
| NGC 7320a | 22:36:32.2   | +33:47:46     | 6702 ± 24              | 360                           | 6.3 ± 0.2                    |
| Anon 7    | 22:35:19.3   | +34:08:00     | 6654 ± 16              | 160                           | 2.2 ± 0.5                    |