

docking a fragment of the hisP to the NBD density. The initial experimentally phased electron density map revealed eight monomers of Eco-msbA with real-space correlation coefficient ranging from 36 to 64% between monomers. Eightfold noncrystallographic symmetry averaging, solvent flattening/flipping, phase extension, and amplitude sharpening were accomplished using locally written software (G. Chang, unpublished data) and yielded electron density maps that were of excellent quality for model building. The final inversion R value of 38% reflects the relatively large solvent content, the intensity distribution of the data, the disorder due to the missing regions of the molecule, and the presence of detergent in the crystal.

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33. Numerous rounds of vector refinement were performed using the program XPLOR to best fit the model into the sharpened electron density. Using this preliminary model, anisotropic correction to the diffraction was applied using XPLOR. Wilson plots indicated a sharp drop of the mean diffraction intensities as a function of resolution with an overall B factor for the data ~ 150 Å².
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38. Multicopy refinements were done using 5, 8, 10, or 16 copies of the asymmetric unit. These multicopy refinements yielded similar crystallographic R factors (27%), R_{free} values (38%), and averaged model structures. The significant drop in the R_{free} value during the multicopy refinements and the similarity of the independently averaged model structures suggested a proper fit of the data. The choice of using 16 copies of the asymmetric unit provided an opportunity to more finely observe their spatial distribution. Helical regions were more similar while loop regions were generally more disordered. B factors for all atoms were fixed at 90 Å² during the multicopy refinement. An image of superimposed models (C_{α} traces) generated from the multicopy refinement can be found on Science Online (www.sciencemag.org/cgi/content/full/293/5536/1793/DC1).
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56. Single-letter abbreviations for the amino acid residues are as follows: A, Ala; C, Cys; D, Asp; E, Glu; F, Phe; G, Gly; H, His; I, Ile; K, Lys; L, Leu; M, Met; N, Asn; P, Pro; Q, Gln; R, Arg; S, Ser; T, Thr; V, Val; W, Trp; and Y, Tyr.

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Hydrogen 21-Centimeter Emission from a Galaxy at Cosmological Distance

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We have detected the neutral atomic hydrogen (HI) emission line at a cosmologically significant distance [redshift (z) = 0.18] in the rich galaxy cluster Abell 2218 with the Westerbork Synthesis Radio Telescope. The HI emission originates in a spiral galaxy $2.0 h_{65}^{-1}$ megaparsecs from the cluster core. No other significant detections have been made in the cluster, suggesting that the mechanisms that remove neutral gas from cluster galaxies are efficient. We infer that fewer than three gas-rich galaxies were accreted by Abell 2218 over the past 10^9 years. This low accretion rate is qualitatively consistent with low-density cosmological models in which clusters are largely assembled at $z > 1$.

Galaxies in clusters have evolved in the past $\sim 3 \times 10^9$ years. The number of blue galaxies in clusters was higher in the past (the Butcher-Oemler effect) (*1, 2*) and spi-

ral galaxies were more prevalent (*3–5*). It has been argued that these effects are caused by enhanced accretion of gas-rich star-forming galaxies from the surrounding field (*6–8*). Detailed modeling suggests that the neutral gas disks of infalling galaxies can be stripped by the hot x-ray gas that envelopes rich galaxy clusters (*9–11*). Because the neutral gas provided the fuel for star formation, the star formation rate drops precipitously after the cold gas has been removed. Hence, galaxies rapidly fade and redden after they have been accreted by a

rich cluster. The low neutral atomic hydrogen (HI) content of galaxies in the cores of the nearby Coma (*12*) and Virgo (*13*) clusters is consistent with these models. However, at higher redshift, at which the galaxy accretion rate is predicted to be higher and spiral galaxies are more abundant in the central regions of rich clusters, these models have not been tested by direct observations of the neutral gas reservoir of infalling galaxies. Studies of HI at an emission line of 21 cm wavelength have been limited to the local universe (*12–15*), because radio synthesis telescopes were not equipped to operate at frequencies corresponding to the redshifted HI line or lacked the sensitivity to detect the HI line at higher redshifts.

We have initiated a program of deep HI imaging of galaxy clusters Abell 2218 and Abell 1689 at redshift (z) ~ 0.2 to study the content and distribution of HI in cluster galaxies at intermediate redshifts. Here, we report on observations of Abell 2218 at $z = 0.176$ from the recently upgraded Westerbork Synthesis Radio Telescope (WSRT). The cluster is extremely rich and massive (*16, 17*), has a luminous and extended x-ray halo (*18*), and has become widely known for the Hubble Space Telescope imaging that revealed a rich structure of strong gravitational arcs (*19*).

Observations were performed with the WSRT during the commissioning of the upgraded system in the period from July to

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September 1999. Data were taken with the cooled 21-cm receivers in two adjacent bands of 10 MHz each, thus producing 2×128 channels each of 78.1 kHz, corresponding to a velocity spacing of 19.5 km s^{-1} at the redshift of the cluster and a resolution of 38.9 km s^{-1} after Hanning smoothing. Each frequency band was observed for 18×12 hours, while the positions of the four movable telescopes were varied. The results reported here are based on the analysis of the usable 60% of the data (20). The data were taken around 1200 MHz, which is outside the protected frequency bands for radio astronomy. As a result, the data were affected by human-made interfering signals, and careful inspection and editing of the data were essential. The spatial resolution in the final data set is $18.0'' \times 19.7''$ arc sec and the root mean square (rms) noise level after Hanning smoothing is 0.11 millijansky per beam (mJy/beam) in the lower frequency band and 0.10 mJy/beam in the higher frequency band. The bandwidth and the primary beam [$7 h_{65}^{-1}$ megaparsecs (Mpc) diameter at full width at half maximum (FWHM)] together define a total survey volume of $\sim 2500 h_{65}^{-3} \text{ Mpc}^3$ [$h_{65} = H_0/(65 \text{ km s}^{-1} \text{ Mpc}^{-1})$, where H_0 is the Hubble constant].

The most prominent signal in our data set amounts to 8σ , with optimal smoothing using a Gaussian filter with FWHM = $20''$ in the spatial domain and FWHM = 60 km s^{-1} in the frequency domain (Fig. 1). No other significant ($>6\sigma$) signals were found, neither in the full-resolution nor the smoothed versions of the data cube. The integrated flux in the detection, corrected for primary beam attenuation, is 33 mJy km s^{-1} . This is equivalent to an HI mass of $(5.4 \pm 0.7) \times 10^9 h_{65}^{-2}$ the mass of the sun ($M_\odot$), which is less than the typical HI mass of a field galaxy ($M_{\text{HI}}^* = 8.4 \times 10^9 h_{65}^{-2} M_\odot$) (21). The velocity width of the detected emission line is small, $60 \pm 20 \text{ km s}^{-1}$ at 50% of the peak flux. The narrowness of the signal explains why this modest HI mass stands out from the noise. The redshift of the HI line is $z = 0.1766$, coincident with the peak in the redshift distribution of the confirmed cluster members (17).

To confirm the signal and to investigate the properties of the source, we used the Keck telescope to obtain optical imaging and spectroscopic observations of the source responsible for the HI emission. The optical image with HI contours overlaid (Fig. 2) shows that the HI emission coincides with a spiral galaxy that has two well-developed bluish spiral arms emanating from a redder and elongated north-northeast- and south-southwest-oriented barlike structure. The western spiral arm runs along and extends beyond a redder

companion galaxy $\sim 18 h_{65}^{-1} \text{ kpc}$ to the southwest. We christened the HI-selected spiral galaxy A2218-H1. The J2000 coordinates of A2218-H1 are $\alpha = 16:33:58.5$ and $\delta = +66:10:06$. From the imaging observations we infer that the apparent red magnitude (R) = 18.9 ± 0.1 for the spiral galaxy, which means that its intrinsic luminosity is about half that of the Milky Way Galaxy. For the companion galaxy, we find $R = 19.9 \pm 0.1 \text{ mag}$. Our spectroscopic observations (Fig. 1) show that the optical redshift of A2218-H1 is $z = 0.1766 \pm 0.0001$ and that of the companion galaxy is $z = 0.1768 \pm 0.0002$, thus giving a velocity separation of $50 \pm 60 \text{ km s}^{-1}$. Both redshifts are within 1σ of the redshift of the HI detection. This confirms the identification and suggests that the spiral and its companion galaxy are interacting. Because of the limited spatial resolution of the HI measurements, we cannot exclude the possibility that the companion galaxy contributes to the total measured HI signal, although the small velocity width of the HI

line suggests that the HI signal originates in a single galaxy.

The optical spectra indicate that A2218-H1 and its companion galaxy have evolved stellar populations and a low star formation rate, although the spiral arms of A2218-H1 are too faint to contribute much to its optical spectrum. The galaxies are not detected in our deep 1200-MHz continuum map (rms noise, $29 \mu\text{Jy}$), which provides a 3σ upper limit to the star formation rate (22) of $1.4 M_\odot/\text{year}$. By comparison, the current star formation rate of the Milky Way Galaxy is about $4 M_\odot/\text{year}$ (23). Nearby interacting galaxies in the field at $z = 0$ generally show much higher star formation rates (24), probably because the gas experiences shock wave heating during the interaction (25). Apparently, star formation is inhibited, even though all the conditions for a strong star burst seem to be met: sufficient fuel and an interaction to trigger the burst.

A2218-H1 does not show indications of the influence of interaction with the intra-cluster medium (ICM). The gas richness is

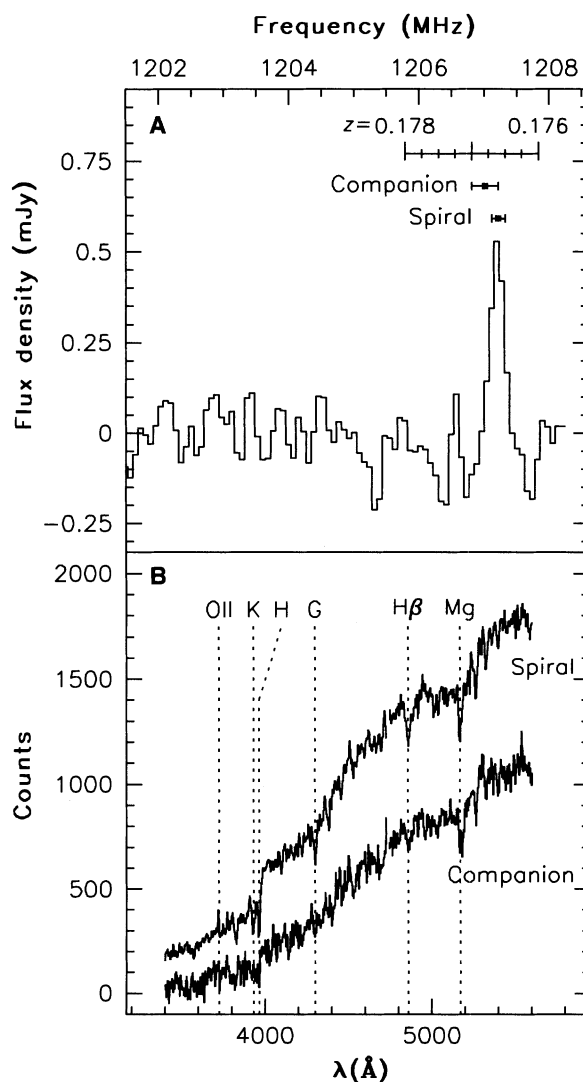
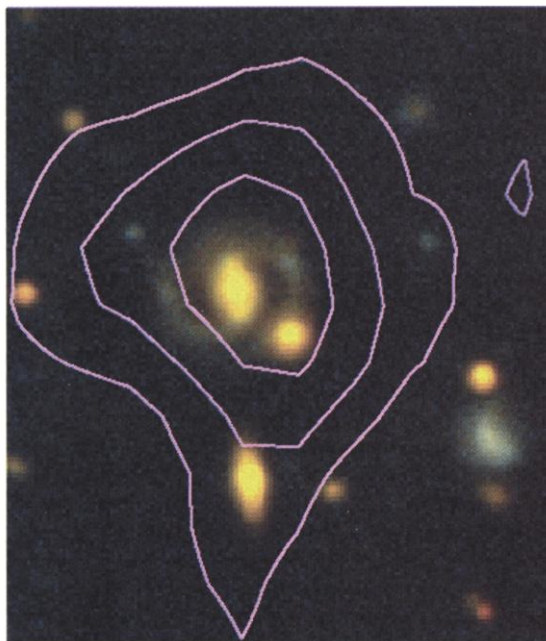


Fig. 1. Spectra of the first HI selected galaxy at $z = 0.18$. (A) The global HI profile. It is Hanning smoothed, which results in a spectral resolution of 38.9 km s^{-1} . The optical redshifts of the spiral galaxy and its companion are also indicated, with 1σ uncertainties. (B) The optical spectra of the spiral galaxy A2218-H1 and its companion. λ , wavelength. The spectra were obtained on 31 March 2000 with the Low-Resolution Imaging Spectrometer (30) on the W. M. Keck I Telescope with the 300 lines/mm grating and a $1''$ slit. A2218-H1 was observed for 800 s and its companion galaxy for 300 s, both during twilight. The redshift of A2218-H1 is $z = 0.1766 \pm 0.0001$ and that of the companion galaxy is $z = 0.1768 \pm 0.0002$, thus giving a velocity separation of $50 \pm 60 \text{ km s}^{-1}$. Both redshifts are within 1σ of the redshift of the HI detection. OII, K, H, G, Hβ, and Mg indicate the identified spectral features.

Fig. 2. Overlay of HI contours on a color representation of the optical image. The contours correspond to $1.2 \times 10^{19} \text{ cm}^{-2}$, $1.9 \times 10^{19} \text{ cm}^{-2}$, and $2.5 \times 10^{19} \text{ cm}^{-2}$. In this image, the FWHM of the Westerbork synthesized beam is $18.0'' \times 19.7''$, comparable to the extent of the second contour. The optical imaging observations were obtained on 4 April 2000 with the Echelle Spectrograph and Imager on the W. M. Keck II Telescope. The field was observed for 300 s in the *R* band and for 300 s in the *B* band. The seeing was $0.9''$. The size of the image is $46'' \times 53''$, which corresponds to $141 \times 163 h_{65}^{-1} \text{ kpc}$ at the redshift of Abell 2218.



typical of field spiral galaxies (26) (gas-to-luminosity ratio $M_{\text{HI}}/L_R = 0.3$), and within the positional accuracy of 20 kpc we detect no offset of the HI distribution with respect to the stellar disk. The most sophisticated models of accretion onto clusters consist of three-dimensional smooth particle hydrodynamics (SPH) simulations of spiral galaxies with a complex multiphase structure (11). These simulations predict that the HI disk of A2218-H1 will be stripped completely in 10^8 years after the galaxy enters the ICM. The position of A2218-H1 is about 11 arc min west from the central super giant elliptical (cD) galaxy, which also marks the peak of the x-ray profile. This separation translates to a projected distance of $2.0 h_{65}^{-1} \text{ Mpc}$ from the cluster core. The detected galaxy therefore resides in the outskirts of the cluster, beyond the point where the bright x-ray halo (18) has been measured. The small radial velocity difference between the cluster center and the galaxy, in combination with the large projected distance, suggests that the galaxy is currently infalling onto the cluster with a high radial acceleration. If the galaxy is on a trajectory toward the cluster core, it will probably enter the ICM in $\sim 2 \times 10^8$ years (27).

Abell 2218 displays a moderate Butcher-Oemler effect: The blue galaxy fraction in the core of the cluster is 11% (1). None of these blue galaxies have been detected in our 21-cm observations, providing an average upper limit of $5.0 \times 10^9 h_{65}^{-2} M_\odot$ on the HI mass of individual galaxies in the blue Butcher-Oemler population, assuming a velocity width of 100 km s^{-1} . Although the brightest of the galaxies responsible for

the Butcher-Oemler effect have luminosities comparable to those of normal field spiral galaxies (1), they must have lower gas-to-luminosity ratios. The low HI content of this extremely rich Butcher-Oemler cluster provides support for current SPH models of the effects of ram pressure stripping on the cold gas disks of galaxies. In addition, the lack of a significant population of HI-rich galaxies in the outskirts of Abell 2218 implies that it has a low accretion rate of gas-rich field galaxies at the observed epoch. Using the fact that the survey is sensitive to galaxies with HI masses larger than M_{HI}^* throughout the primary beam, and the assumption that HI disks of infalling galaxies remain undepleted at distances from the cluster core larger than that of A2218-H1, we can derive a 95% confidence upper limit to the accretion rate (28) of 3×10^9 years. We conclude that there is no large reservoir of gas-rich galaxies that might form a future Butcher-Oemler population, consistent with the low Butcher-Oemler effect observed at $z = 0$. The low accretion rate of this massive cluster at $z \sim 0.2$ is in qualitative agreement with low-density cosmological models in which clusters are largely assembled at $z > 1$ (6, 29).

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27. Here, we assume that A2218-H1 has an infall velocity equal to the velocity dispersion of the cluster of 1370 km s^{-1} and has to travel $\sim 300 \text{ kpc}$ to the edge of the detectable x-ray halo.
28. The galaxy A2218-H1 shows no signs of stripping, so we can safely assume that the HI reservoirs of galaxies at distances from the cluster center larger than that of A2218-H1 are not depleted. The annulus over which an infalling $M_{\text{HI}} > M_{\text{HI}}^*$ galaxy could be detected is therefore defined by the radius of the primary beam and the radius of A2218-H1. The width of this annulus is 2 Mpc. The maximum velocity of an infalling galaxy equals the velocity dispersion of the cluster, which is 1370 km s^{-1} . The minimum time that such a galaxy would be detectable is therefore 1.5×10^9 years. Poisson statistics and the fact that only one galaxy is detected give a 95% upper limit to the number of galaxies within this annulus of 4.5. The 95% upper limit to the infall rate is therefore 3.1×10^9 years. This calculation is based on the assumption that A2218-H1 and the cluster core are at the same distance from the observer.
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