HI 2334+26: An Extended HI Cloud near Abell 2634

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ABSTRACT

We report the serendipitous discovery of a large HI cloud with an associated HI mass of $6(\pm 1.5) \times 10^9 h^{-2}$ $M_\odot$ and a heliocentric velocity 8800 km s^{-1} , located near the periphery of the cluster of galaxies Abell 2634. Its velocity field appears to be very quiescent, as no gradients in the peak velocity are seen over its extent of $143h^{-1}$ by $103h^{-1}$ kpc. The distribution of gas is poorly resolved spatially, and it is thus difficult at this time to ascertain the nature of the cloud. At least two relatively small, actively star–forming galaxies appear to be embedded in the HI gas, which may (a) be an extended gaseous envelope surrounding one or both galaxies, (b) have been spread over a large region by a severe episode of tidal disruption or (c) have been affected by the ram pressure resulting from its motion through the intracluster gas of A2634.

Subject headings: Normal galaxies, Groups, Intergalactic Matter

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1. Introduction

Atomic hydrogen in a galaxy is a convenient tracer of the potential for future star formation and a probe of the kinematical field. Because normal spiral galaxies contain an amount of HI predicted by their optical radii (see reviews by Giovanelli & Haynes 1987; Roberts & Haynes 1994, and refs. therein), the neutral hydrogen content of a spiral galaxy is a suggestive indicator of disturbances in the galaxy's evolutionary history. Collisions, tides and intracluster interactions can remove gas, lowering a disk galaxy's HI content or possibly create a star–forming disk in a system previously without one. In the case of tidal interactions and gas sweeping, the HI distribution can also provide a glimpse of the disruptive event as the gas, removed from its normal disk location, is flung to large distances. Numerous examples (see refs. above) exist of HI displaced from the parent galaxy by such processes. In many instances the mapping of the HI distribution provides the clues needed to constrain simulations of the disruptive event (e.g. Stanford & Balcells 1991; Smith 1994).

Extended HI distributions may also indicate the relative youth of systems still in the process of collapse. In I Zw 18, whose youth is reflected in its extreme low metal abundance, the compact starbursting components are embedded in a much larger HI envelope (Viallefond *et al.* 1987; Lequeux & Viallefond 1980). HI 1225+01 is formed by two main HI condensations, one of which is associated with an actively star forming blue dwarf galaxy. The other condensation emits no detectable starlight (Giovanelli *et al.* 1991). It can be speculated that the optically visible component has only recently breached the star formation threshold (Chengalur *et al.* 1994). Taylor *et al.* (1993) further hypothesize that the star formation events in blue compact dwarfs are triggered by interactions with nearby HI companions.

Although less clearly traceable, the link between extended HI distributions, star formation and the formation of disks has also been discussed in scenarios of severe tidal disruption and merging. Some active galaxies are seen to be embedded within a more extensive HI distribution (see for example Heckman *et al.* 1982). Appleton *et al.* (1990) show evidence of the formation of a disk parallel to the minor axis within the elliptical NGC 5903 as the result of recent accretion. Barnes & Hernquist (1992) have suggested that dwarf galaxies may form in the tidal debris as possibly indicated in such systems as the Antennae (Mirabel *et al.* 1991). In compact groups, HI is often seen displaced from the member galaxies (Shostak *et al.* 1984; Williams & van Gorkom 1988). Williams *et al.* (1991) suggest even further that the HI distribution in compact groups may be a good indicator of the evolutionary stage of the group itself.

Giovanelli & Haynes (1989) have suggested that HI 1225+01, a system with a very large HI–to–optical size ratio, has remained intact due to its relative isolation. Compact groups and clusters, however, present a harsh environment to the thermally fragile HI gas through tidal and dynamical stirring, as well as contact with the hot intracluster medium. While the interpretation of giant HI envelopes may be ambiguous, it is thus surprising to find weakly bound HI clouds of large extent in high density environments.

Here, we report the serendipitous discovery of an extended HI cloud, of unusually large extent, located near the periphery of the cluster of galaxies Abell 2634. Observations of the 21 cm HI line emission and follow–up optical imaging and spectroscopy are presented in Section 2. Although the current HI observations are of inadequate spatial resolution to allow an unambiguous interpretation of the nature and origin of the HI cloud, we briefly discuss in Section 3 possible interpretative outlines. Intrinsic properties are computed for $H_0 = 100h$ km s^{-1} Mpc^{-1}.

2. Observations

In the course of a 21 cm line survey of galaxies in the cluster A2634 undertaken with the 305m telescope of the Arecibo Observatory (Scodeggio *et al.* 1995, hereinafter SSGH; Giovanelli *et al.* , in preparation), we have obtained HI line spectra for a number of previously uncatalogued galaxies identified by us from a visual examination of the Palomar Observatory Sky Survey (POSS) prints to lie in or near the cluster. One such object is a spiral galaxy at RA(1950) = 23^h 33^m 57^s, Dec(1950) = 26° 22.7' — hereinafter referred to as galaxy A — observed and detected in the HI line in July of 1993.

The HI emission spectrum of galaxy A is shown in Figure 1a. In addition to an emission feature identified with the optical galaxy at a systemic heliocentric velocity of 9212 ± 4 km s^{-1} , the spectrum exhibits a feature of comparable flux near V_{hel}=8800 km s^{-1} . When a nearby galaxy at RA(1950) = $23^h34^m16^s$, Dec(1950) = $26°23.1'$— hereinafter referred to as galaxy B — was observed, the same feature at 8800 km s^{-1} was detected again, as illustrated in Figure 1b. The relative intensity at the two positions suggested that the 8800 km s^{-1} feature was extended, and a coarse mapping of the region ensued.

Figure 2 summarizes the results of HI spectra taken at 45 positions on a mapping grid with the Arecibo dual circular 40–foot tunable 22 cm feed. This feed has a half-power beamwidth of 3.3′. Most spectra had an on–line spectral resolution of 8 km s^{-1} , degraded to 16 km s^{-1} after smoothing. The typical rms noise level of each smoothed spectrum is 0.85 mJy. A few observations near the center of the apparent HI distribution were made with a resolution twice as high, e.g. figure 1b. In Figure 2, the locations of observed spectra are indicated by either crosses (no detection) or filled circles (detections); the area within each filled circle is proportional to the integrated flux of the 8800 km s^{-1} feature at each position. Observations coincident with galaxies A and B are labeled, as is that of a third galaxy ("C") to be discussed later. The peak velocity at each position at which HI is detected is indicated under each symbol; associated velocity errors, which are dependent on signal–to–noise ratio, vary between 3 and 20 km s^{-1} , with the larger errors near the cloud periphery. The half–power beam size of the 22 cm feed is illustrated in the figure to emphasize the limited spatial resolution of this set of observations. Because the 22 cm feed is also characterized by the presence of a first sidelobe ring of $5.6'$ in diameter, peaking at about the 10% level of the main beam, caution is necessary in the interpretation of extended emission. Detections are identified only where flux densities are well in excess of what would be expected from sidelobe contamination; by comparison, galaxy A is only detected when the beam is on source or on points less than two thirds of a beamwidth away, as indicated by the square symbols in fig. 2. Contour lines at equal levels of integrated flux per beam are superimposed. In spite of the poor resolution, the HI feature is definitely extended. Approximate deconvolution of the beam smearing effects (see Giovanelli *et al.* 1991 for details) suggests that the HI extends over a region of size about $5.5'$ by $4'$, roughly the outline of the outermost solid contour. The most striking aspect of Figure 2 is the near constancy of the velocity of the HI emission associated with the extended HI. Despite the limitations in spatial resolution of the current map, the continuous but quiescent nature of the velocity field suggests that the extended HI distribution may be a single diffuse structure seen close to face–on. In the following, therefore, we refer to the extended HI distribution as "the HI cloud".

In the course of a direct imaging run made in poor photometric conditions, two images centered on the cloud position (1800 s exposure at B and 600 s exposure at I band) were obtained in September 1993 with the 1.3m telescope at the MDM observatory, equipped with a Loral 2048 $\times$ 2048 CCD chip. On–chip rebinning by a factor of two yields images with a scale of $0.64''$pixel^{-1}, covering a field of $10.9'$ on a side. As shown in Figure 3, the blue image of the field contains several galaxies with angular sizes between $10''$ and $20''$; the sky density of such objects is quite high and is related both to the nearness to the center of A2634 and to the presence of a background cluster (see SSGH).

Galaxies with identification labels in Figure 3 were among the targets of spectroscopic observations in the A2634 region obtained using the 2.4m telescope at the

MDM observatory in September 1993. The spectrograph was equipped with a Loral 2048×2048 CCD chip and a low dispersion grating (300 lines mm^{-1}), giving spectral coverage of the region between 4500 and 8000 Å. Spectra with signal–to–noise ratios adequate for redshift measurements were obtained for 38 galaxies, as listed in Table 1. Reduction followed standard procedure using IRAF[2]. tasks. Each frame was overscan- and bias-subtracted, then flat-fielded using appropriate dome flats. Wavelength calibration was performed using HeNeAr comparison spectra. Heliocentric velocities were computed in two different ways, depending on the emission or absorption line nature of the spectrum: using the IRAF task *fxcor*, that is based on the cross-correlation algorithm described by Tonry & Davis (1979), for E and S0 galaxies; and measuring the central wavelength of the gaussian fit to the emission lines of spiral galaxies (typically between 3 and 5 lines were measured for each galaxy). Three different K giant stars were used as templates for the cross-correlation.

Radial velocities have been obtained for several galaxies in Table 1 also by Pinkney *et al.* (1993). The redshifts given for the three galaxies A, B and C by those authors differ significantly from the ones reported here; Pinkney *et al.* obtain for galaxies A, B and C respectively 12205, 9203 and 6759 km s^{-1} . It should be noted that the uncertainty of these former measurements is rather large, because of limited signal to noise ratio in their spectra (see Pinkney *et al.* for a discussion of their class C2 redshift determination, and SSGH for a broader comparison of our data and those of Pinkney *et al.*), and because their spectral coverage did not extend far enough to the red to include the Hα line. Note that our redshift for galaxy A is obtained from the HI spectrum shown in Figure 1a, while the two other galaxies show such strong Hα that the optical redshift we derive is certain.

Among the galaxies projected on the HI cloud, those identified as A,B,C,E and G have velocities that make them likely members of A2634. Indeed, the HI emission found at the position of galaxies B and C cannot be separated into components associated with the galaxy disks and the extended cloud. Three other galaxies with measured velocities near 35,000 km s^{-1} are probably member of a background cluster (Pinkney *et al.* 1993; SSGH). There are several other faint galaxies projected on the region of HI emission, but unfortunately no radial velocities are available for these objects.

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3. Discussion

3.1. System Parameters

As discussed above, we interpret the extended HI emission as a single coherent structure subject to the caveat of the limitations of the current HI map. Because of its position and velocity, it is reasonable to assume that the HI cloud is bound to the cluster A2634, but likewise, there is some ambiguity in interpreting the redshift of the HI cloud directly in terms of its distance. The cluster center, RA(1950) = $23^h35^m55^s$, Dec(1950) = $26°44'19''$, lies about half a degree to the northeast of the cloud center. For A2634, SSGH obtain a heliocentric systemic velocity of 9240 km s^{-1} and a velocity dispersion of 661 km s^{-1} . Therefore, any object at the position of the cloud with a velocity between 8000 and 10,500 km s^{-1} is very likely a cluster member (see SSGH for a detailed discussion on cluster membership). Assuming that A2634 is at rest with respect to the reference frame of the cosmic microwave background radiation, the HI cloud would have a distance of $89\,h^{-1}$ Mpc. Alternatively, it could be located at its redshift distance of $84\,h^{-1}$ Mpc in the foreground of the cluster, or it could be a background object with a significant infall velocity. In the following we derive sizes, masses and luminosities assuming the HI cloud and the galaxies most closely associated with it are at the cluster distance.

The rough extent of the cloud is $143h^{-1}$ by $103\,h^{-1}$ kpc; the HI mass is $M_{\rm HI} = 6(\pm 1.5) \times 10^9\,h^{-2}$ M$_\odot$. Most noticeable is the constancy in the mean velocity of the HI and the narrowness of the HI line which, measured at the half–power points, is also seen to be remarkably constant about 140 km s^{-1} . It is to be emphasized that while the low spatial resolution of the beam is expected to smear any existing velocity gradients, a systematic difference in the mean velocity between opposite sides of the HI at a level greater than 20 km s^{-1} would be easily detected by these HI observations. For example, the receding and approaching sides of galaxies significantly smaller than the beam are easily identified by applying half beam pointing offsets.

The properties of galaxies A,B and C are summarized in Table 2. Because the photometric quality of the MDM images is poor, we are unable to assign absolute values to magnitudes and colors of the objects in the field. We estimate the blue total magnitude of galaxy A to be on the order of 16.3 ± 0.2, on the basis of visual inspection of the Palomar Observatory Sky Survey plates and of digitized images of the "Palomar Quick Survey" obtained from the Space Telescope Science Institute Archives, kindly assisted by Dr. D. Golombek. Galaxy B is about 0.65 B mag fainter and galaxy C 0.70 mag fainter than galaxy A; galaxy C also appears to be 0.2 mag bluer than A and B (in $B-I$). Isophotal sizes of the 3 galaxies at the approximate level of $\mu_B \sim 26$ mag arcsec^{-2} are also estimated; these values are listed in Table 2. For $h=1$, the distance modulus of A2634 is 34.7; therefore these galaxies are about 3 mag fainter than the knee of the luminosity function M_*.

The velocity separation between galaxy A and the HI cloud at 8800 km s^{-1} is large (>400 km s^{-1}) and it is therefore likely that no relation exists between the two. The other two galaxies – B and C – have optical radial velocities undistinguishable from that of the HI cloud and lie within its boundaries. For objects bound to a cluster, coincidence in projected position and velocity is not necessarily equivalent to spatial proximity. However, both objects exhibit unusually strong emission lines in their optical spectra. In Table 2, the equivalent widths of Hα+ [NII] are significantly larger than those expected for normal spiral galaxies (Kennicutt & Kent 1983). This implies strong star formation activity, which requires large supplies of gas. The association of galaxies B and C with the HI is therefore likely. It is relevant to note the association of extended HI clouds with regions of active star formation bursts in diverse objects like I Zw 18 (Searle & Sargent 1972) and HCG 18 (Williams & McMahon 1988).

The extent of the HI is large in comparison with the sizes of the optical disks or even with the projected separation of galaxies B and C on the plane of the sky, which is only $55\,h^{-1}$ kpc. The $M_{\rm HI}/L_B$ ratio, even when we add the luminosity contribution of both galaxies, yields a value of 1.6. Typical values for field galaxies range between 0.2 and 0.5, for spirals (Roberts & Haynes 1994); a value of 1.6 is found only in the upper quartile of the latest types, Sm/Im. Other systems contain comparable amounts of HI distributed across similar extents. The quiescent cloud in HCG 18 has a diameter of 37.5 h^{-1} kpc and an HI mass of $6\times10^9\ h^{-2}$M$_\odot$ (Williams & van Gorkom 1988). For comparison, HI 1225+01 contains $4.9\times10^9\ h^{-2}$M$_\odot$ of HI over an extent of ~ 215 h^{-1} kpc (Giovanelli *et al.* 1991). Comparatively, the size and mass of the HI cloud in Abell 2634 are high, though not uniquely so.

3.2. Interpretative Scenarios

We consider three possible interpretations of the origin of the HI cloud. First, we assume that B and C are two gas–rich galaxies currently undergoing an encounter that results in tidal fireworks of the type described by Toomre & Toomre (1972). Tides and collisions are the suggested cause of the offset HI distributions seen in Stephan's Quintet (Allen & Sullivan 1980; Shostak *et al.* 1984). In a second scenario, the two galaxies are embedded in a common gaseous envelope of the type seen in the giant Virgo cloud HI

1225+01 (Giovanelli *et al.* 1991; Chengalur *et al.* 1994). Such a cocoon scenario has also been suggested for the interpretation of HCG 18 as a single amorphous galaxy (Williams & van Gorkom 1988). In a third, the HI associated with either galaxy B, C or both, is recently swept by the ram pressure of the intracluster medium in A2634 not unlike the case of NGC 1961 (Shostak *et al.* 1982).

All interpretations have to contend with the lack of Doppler gradients in the gas, as if the relative motion of the two galaxies and the internal motions within each occurred largely in the plane of the sky. Such a velocity field is reminiscent of the HI cloud in HCG 18 (Williams & van Gorkom 1988) but quite unlike that seen in Stephan's Quintet (Shostak *et al.* 1984) or Seyfert's Sextet (Williams *et al.* 1991).

While we cannot separate the cloud and galaxy emission in the direction of objects B and C, we can nonetheless ask whether it is plausible that the galaxies are embedded in the cloud by comparing their expected velocity spread with that observed in the HI emission at those locations. We can crudely estimate the magnitude of internal motions in the two galaxies using the luminosity–HI line width relation. For example, for galaxy A, the observed width of 182 km s^{-1} converts to about 275 km s^{-1} after applying a correction for inclination; this value and that of the magnitude in Table 2 agree well with the luminosity–HI line width relation in Haynes & Giovanelli (1984). Using the same relation, one should expect widths of about 225 km s^{-1} for galaxies B and C which, after correction for inclination should be observed between 160 and 190 km s^{-1} . While somewhat higher than the observed HI widths, the expected values are not untenably high, and therefore internal motions in the galaxies may occur within the range of velocities of the observed line widths. On the edges of the HI cloud, however, one should expect the gas to have a lower velocity dispersion than in the region occupied by the galaxies. Figure 4 displays an east–west cut of the velocity field, which crosses over the position of galaxy C. While emphasizing again the constancy of the mean velocity in the field, it also hints at a broadening of the HI line widths near RA = $23^h34^m10^s$, the location of galaxy C, and to the east.

In the cocoon scenario, the fact that neither of the two galaxies (especially galaxy B) lies in the region of highest column density for the gas must be explained. One may argue that only galaxy C is associated with the HI gas and somewhat force the issue by attributing the (smaller) offset of C from the center of the gas to poor telescope pointing (which cannot be totally excluded, although observations were made over a wide range of altazimuthal configurations and a systematic pointing offset would not likely be present in the map), and assume that B is an interloper seen closeby only in projection. The strong emission lines in the spectrum of B however suggest the presence of a fresh supply of gas.

The tidal scenario is likewise plausible, but the circumstance of a "flat" velocity field to a couple of tens of km s^{-1} or less requires a very special geometry for the encounter. This model can handle better the offset of the galaxy positions from the HI peak, if most of the gas is visualized as initially associated with one of the two galaxies (possibly C). Given the small separation of the two galaxies, tidal damage can be significant, especially if the gas was loosely connected to the parent galaxy (e.g., in an extended disk) to start with. Since the center of the HI cloud appears offset from both galaxies, the interaction would have been of an exceptionally disruptive nature, although no morphological signature of tidal distorsion is evident in the CCD image.

It is relevant to underscore that the space density of galaxies in this region is significantly enhanced, and that all galaxies between 8000 and 10,500 km s^{-1} in the region are well within the most conservative set of caustics for the cluster A2634 (SSGH). Within a $20'$ radius from galaxy C, two kinematically separate groups of galaxies are identifiable: 9 objects with velocities between 8300 and 9000 km s^{-1} , and 8 with velocities between 9200 and 9700 km s^{-1} , with a clear gap in between. Both groups are spiral rich, and are presumably falling for the first time toward the cluster center, where the loosely bound HI material is unlikely to retain any association with individual galaxies, whether it is now in the form of an extended envelope or of tidal appendages. This dynamical circumstance and the symmetry of the HI distribution, vis–a–vis the direction to the cluster core, suggest the possibility that the positional offset of the HI cloud and the galaxy or galaxies initially associated with it may result from the interaction of the cold HI with the intracluster medium associated with A2634. The ram pressure stripping model of Gunn & Gott (1972; eq. [62]) provides an estimate of the expected efficiency of ram pressure ablation on galactic disks. From the Eilek *et al.* (1984) hydrostatic equilibrium model of the hot gas distribution in A2634 (for an X-ray map see fig. 17 of SSGH), we infer a mass density of gas at the position of galaxy C of $2.2 \times 10^{-29} h^{1/2}\,\mathrm{g\,cm^{-3}}$, while the mean disk restoring force of a typical spiral is $1.0 \times 10^{-11}\,\mathrm{dyn\,cm^{-2}}$. The ratio of these two quantities implies that, for ram pressure stripping to be effective, the component of the velocity of the galaxy C perpendicular to its disk should be $\sim$ 100 times larger than its observed velocity offset (424 km s^{-1} in the reference frame of the cluster), or that the gravitational force binding the gas to the galaxy should have a value $\sim$ 100 times smaller than the one adopted here. As in the case of NGC 1961 (Shostak *et al.* 1982; Gottesman *et al.* 1983), the possibility of stripping is not easily explained but cannot be ruled out.

Whichever the current configuration of the gas may be, this system appears destined for further dramatic changes. Planned synthesis observations should soon help to clarify the picture, when further speculations will be better justified.

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Figure 1: (a) HI profile taken at the position of galaxy A, with a channel separation of 8 km s^{-1} . The emission of the galaxy is the feature at V_{hel} = 9212 km s^{-1} , while that of the extended HI is centered near V_{hel} = 8800 km s^{-1} . The downgoing feature near 8500 km s^{-1} is poorly subtracted man–made interference (GPS satellite system). (b) HI line profile taken at the location of the peak column density of the extended HI source, with a channel separation of 4 km s^{-1} .

Figure 2: Map of the HI emission. Solid symbols identify detections of HI emission; the area of each circle is proportional to the integrated flux density within the beam, with the largest observed value being 1.89 Jy km s^{-1} . The mean velocity between the half–intensity points, is displayed under each symbol with well measured emission. Small crosses identify positions where no detection was obtained, at a level above 0.25 Jy km s^{-1} . Solid contour intervals correspond to levels of 1.2, 0.9 and 0.6 Jy km s^{-1} per beam, while the dashed one is at 0.35 Jy km s^{-1} per beam. Unfilled squares identify positions at which detection of the emission associated with galaxy A near 9200 km s^{-1} is seen; the area of each symbol is again proportional to the integrated flux density; note that the detectability of galaxy A falls off rapidly from the central position. The position of galaxies A, B and C is identified.

Figure 3: *B* band image obtained at MDM Observatory, flat fielded but photometrically uncalibrated. Scale is 0.64" per pixel. Galaxies with known redshifts, as listed in Table 1, are labeled.

Figure 4: Cut through the velocity field of the HI gas, at the indicated constant value of the declination, slightly to the South of galaxy C, which is at RA = $23^{\mathrm{h}}\ 34^{\mathrm{m}}\ 11^{\mathrm{s}}$. Contour levels are at 1, 2, 3, 4, 5, 6, 8, 10 and 12 mJy. The lowest (outermost) level is barely above the typical rms noise.