GALACTIC RECYCLING: THE H\textsubscript{I} RING AROUND NGC 1533.

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Abstract

We report the discovery of a new H\textsubscript{I} ring around the S0 galaxy NGC 1533. The ring orbits at a radius of 35 kpc, well outside the optical extent of the galaxy. We have conducted N-body/SPH numerical simulations to show this H\textsubscript{I} ring could be the merger remnant of a tidally destroyed galaxy. We find no optical component associated with the H\textsubscript{I} ring. However, observations hint at H\textalpha emission associated with the SE part of the ring only. The H\textalpha is in the form of a few very small isolated emission line regions. The large H\textsubscript{I} velocity dispersions (up to 30 km s\textsuperscript{-1}) and velocity gradients (up to 50 km s\textsuperscript{-1}kpc\textsuperscript{-1}) in this region indicate the H\textalpha emission could be due to star formation triggered by clouds colliding within the ring.

1. Introduction

In the local Universe galaxies continue to interact and merge. These mergers provide feedback into the intergalactic medium; either directly or via star formation. S0 galaxies are synonymous with non-regular H\textsubscript{I} distributions - leading to the common perception that this gas was acquired via accretion or mergers. Simple passive evolution of elliptical and S0 galaxies is inconsistent with observations. To explain the observations, merging and star formation in these galaxy types must have occurred from $z \sim 1$ to the present (Kauffmann, Charlot & White 1996). In contrast to early-type spirals, S0 galaxies exhibit a wide range of $M_{\text{HI}}$-to-$L_B$ ratios. Wardle & Knapp (1986) argue this is evidence for an external origin of H\textsubscript{I} in S0s. This acquisition of H\textsubscript{I} is perhaps more
notable in S0s, since their intrinsic H\textsc{i} content is low. Similar events in spiral galaxies may not be detected as easily.

The formation of H\textsc{i} rings are rare. Rings are known around individual galaxies such the spiral galaxy NGC 628 (Briggs, 1982) and the elliptical galaxy IC 2006 (Schweizer, van Gorkom & Seitzer 1989). H\textsc{i} rings are also found in galaxy groups enclosing more than one galaxy, for example, the M96 group (Schneider, 1985) and the galaxy group LGG 138 (Barnes, 1999). The Cartwheel galaxy, in the H\textsc{i}-rich Cartwheel group, also exhibits an H\textsc{i} ring (Higdon 1996).

Explanations for each of these rings invariably involves some form of merging or accretion. The origin of NGC 628’s H\textsc{i} ring is uncertain, but the absence of a massive companion points toward the acquisition of a gas-rich dwarf galaxy. The H\textsc{i} ring around IC 2006 is thought to be the remnant of the merger that created the elliptical or perhaps a later accretion event. Barnes (1999) proposed the H\textsc{i} ring in LGG 138 was created by a gas-sweeping collision between one of two bright galaxies and an intruder. Analysis of the ring in the M96 group is complicated by the number of galaxies in the vicinity. The distribution of H\textsc{i} in M96 itself suggests it is interacting with the ring and perhaps accreting H\textsc{i} onto its own faint optical outer ring. The Cartwheel galaxy is believed to have formed from a small late type spiral with a large low surface density gas disk. Higdon (1996) suggests that another member of the group, G3, passed through this disk and ‘splashed-out’ the H\textsc{i} to form the ring.

Optical counterparts to these H\textsc{i} rings are rarer still. A very faint dwarf galaxy, Leo dw A resides in the M96 ring (Schneider, 1989). The H\textsc{i} in LGG 138 aligns with a colour break in stellar populations in the South-western region of the ring. Barnes (1999) suggests this is due to star formation triggered by an expanding density wave, together with the stellar remnant of the intruder. On the other hand, the Cartwheel galaxy was first noted for its remarkable optical ring and the H\textsc{i} observations followed. In this case, the ‘splashed-out’ H\textsc{i} is thought to have caused a propagating burst of massive star formation (Higdon, 1996).

When galaxies collide during a merger, they can produce strong shocks, and stars may then form in the cool, compressed gas behind the shock front. For example, large H\textsc{i} and CO velocity dispersion and gradients, in the youngest star forming regions in the Antennae galaxies, indicate stars were produced by colliding gas clouds (Zhang, 2001). Alternatively, gravitational instabilities can cause collapse and formation of stars. The balance between self gravity, velocity dispersion and the centrifugal force in a disk, leads to a critical surface density, \( \Sigma_{\text{crit}} = \kappa \sigma_v / \pi G \), where \( \kappa \) is the epicycle frequency and \( \sigma_v \) is the velocity dispersion of the gas.
According to the Toomre criterion (Toomre, 1964), large scale star formation occurs when $Q (= \Sigma_{crit}/\Sigma_{gas})$ is less than one. The H\textsc{i} ring in the Cartwheel galaxy satisfies this criterion (Higdon, 1996).

Here we present the H\textsc{i} ring surrounding the S0 galaxy NGC 1533. The ring was discovered serendipitously as part of a subset of galaxies from HIPASS (see e.g. Meyer et al., 2002) chosen for mapping with the Australia Telescope Compact Array (ATCA)\textsuperscript{1}. NGC 1533 is located 1° from the centre of the Dorado group. Throughout this paper we assume a distance to NGC 1533 of 21±4 Mpc (Tonry et al., 2001).

2. Observations

NGC 1533 (and consequently its immediate environment) was imaged in 21-cm with the ATCA in three array configurations: the 375, 750D and 1.5D arrays. The dataset was reduced in MIRIAD, it has a restored beam of 68″ × 65″ and a velocity resolution of 3.3 km s\textsuperscript{−1}. The RMS noise in the final cube is 3.7 mJy beam\textsuperscript{−1}, corresponding to a 3σ column density limit, over a typical line width of 40 km s\textsuperscript{−1}, of $3.2 \times 10^{19}$ cm\textsuperscript{−2}.

The H\textsc{i} column density map is overlaid on the DSS image of NGC 1533 in Figure 1a. The H\textsc{i} contours increase linearly from 1.6 to 4.0 $\times 10^{20}$ cm\textsuperscript{−2}. The two smaller galaxies in the NW corner of the image are IC 2039 (closest to NGC 1533) & IC 2038. The higher resolution ATCA image (1.5D array), not included here, clearly shows H\textsc{i} associated with IC 2038, but not IC 2039. The H\textsc{i} ring around NGC 1533 consists of two major components, the NW cloud and the SE cloud. H\textsc{i} gas with column densities below the lowest contour close the ring. No obvious optical counterpart to this ring is seen. The total H\textsc{i} mass of the system (based on the total flux density from HIPASS of 67.6 Jy beam\textsuperscript{−1}km s\textsuperscript{−1}) is $7 \times 10^{9} M_{\sun}$. At its minimum and maximum extent, the radius of H\textsc{i} ring is 2′ and 11.7′ from the optical centre of NGC 1533, corresponding to a projected physical length between 12 and 70 kpc.

Observations of H\textalpha emission in NGC 1533 and surrounds were taken as part of the Survey for Ionization in Neutral-Gas Galaxies (SINGG). Continuum R-band and narrow band H\textalpha images were taken with the CTIO 1.5m telescope. Only one moderate H\textalpha emission line region is seen within the disk of NGC 1533. We also find 5 very small isolated emission line regions in the SE part of the H\textsc{i} ring (see Figure 1b). These emission line regions have H\textalpha fluxes of $1-2 \times 10^{15}$ erg s\textsuperscript{−1}cm\textsuperscript{−2}. At 21 Mpc, this corresponds to H\textalpha luminosities of $5-10 \times 10^{37}$ erg s\textsuperscript{−1}.

\textsuperscript{1}The Australia Telescope Compact Array is part of the Australia Telescope which is funded by the Commonwealth of Australia for operation as a National Facility managed by CSIRO.

H\textsc{i} Ring Around NGC 1533
3. Analysis

Both internal and external origins of the H\textsc{i} ring are considered. If the H\textsc{i} was intrinsic to NGC 1533, it could have been removed via ram pressure stripping by a denser intragroup gas. In this case NGC 1533 would have had a $M_{\text{HI}}$-to-$L_B$ ratio of 1.6, which is plausible for an early-type spiral galaxy. However there is no evidence for a dense intragroup medium in the Dorado group. Also, simulations do not produce the ring-like structure we see.

Alternatively, the H\textsc{i} could have been accreted from another galaxy. IC 2038 and IC 2039 are obvious suspects. The luminosity of these galaxies are 1.5 and $2.6 \times 10^8$ $L_\odot$ respectively. To account for all the H\textsc{i} in the system, these galaxies would had to have had $M_{\text{HI}}$-to-$L_B$ ratios greater than 15, which is not very likely for their morphologies.

The third possibility is the tidal destruction of a galaxy to form a merger remnant around NGC 1533. N-body/SPH numerical simulations were conducted to investigate the orbital evolution of a low surface brightness in NGC 1533’s gravitational potential. The simulated galaxies are based on the Fall-Efstathiou (1980) model. Figure 1c shows the dynamical evolution of the gas in a galaxy approaching on a highly eccentric orbit. The frame is centred on a static potential for NGC 1533. The H\textsc{i} ring forms after $2 \times 10^9$ years ($T=14$) and continues to orbit. The ring-like distribution of gas is also recovered for different orbital entry points and eccentricities. The surface brightness of the stellar remnant is reduced to 26-29 mag arcsec$^{-2}$, which explains why we do not see an optical counterpart. This scenario seems the most plausible explanation for the H\textsc{i} ring. The simulation also lends support to the merger hypothesis for other galaxies with H\textsc{i} rings.

Does this recycled H\textsc{i} gas then form stars? The small H\text{\smaller{a}} emission line regions we see in the SE part of the ring are similar to those reported by Ferguson et al. (1998) in the extreme outer region of disk galaxies. Two star formation scenarios are investigated below.

Firstly, gravitational instabilities in the H\textsc{i} ring could allow stars to form. As described in the introduction, large scale star formation can occur in a disk when $Q < 1$. $Q$ was calculated for every pixel in the 21-cm image. To do this, a tilted ring with p.a.$=140^\circ$ and $i=70^\circ$ was fitted to the H\textsc{i} data and a rotation curve derived. The rotation curve was used to calculate each value of $\kappa$. The velocity dispersion measurement used spectra clipped at 3$\sigma$ to reduce the effect of noise. Not a single pixel was found to satisfy the $Q < 1$ criterion. $Q$ varies from 2 in the densest part of the NW cloud, to greater than 10 in the SE cloud. The large values of $Q$ in the SE region is due to the high velocity dispersions.
This result agrees with the absence of massive star formation in the H\textsc{i} ring, however it fails to explain the H\textalpha emission line regions we do see.

The second possibility is clouds colliding within the ring, condensing the gas and forming stars. The kinematics of the H\textsc{i} local to each H\textalpha emission line region were analysed. H\textsc{i} velocity dispersions were found up to 30 km s\textsuperscript{−1} and velocity gradients in the range 7-50 km s\textsuperscript{−1} kpc\textsuperscript{−1}. The H\textsc{i} velocity profiles of some individual pixels in these region are also ‘double-horned’, indicating expanding or contracting regions of gas. This is in contrast to the H\textsc{i} kinematics in the NW cloud, there the dispersions are mostly less than 10 km s\textsuperscript{−1} and gradients around 2 km s\textsuperscript{−1} kpc\textsuperscript{−1}. These large gas dispersion and gradients are similar to other merger-driver star formation examples such as the young star clusters in the Antennae galaxies.

We conclude that the H\textsc{i} ring around NGC 1533 is most likely the remnant of a tidally destroyed galaxy. Nbody/SPH numerical simulations support this hypothesis. H\textalpha observations show low level star formation in the SE part of the ring. The high H\textsc{i} velocity dispersion and gradients in this region indicate stars may have formed by clouds colliding in the H\textsc{i} ring that is yet to stabilise.

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Figure 1  a) H\textsubscript{i} ring around NGC 1533.  b) SE ring region with H\textalpha\ emission line regions circled.  c) Gaseous components in the simulation.