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Letter to the Editor

Intergalactic neutral hydrogen gas in the Grus quartet of galaxies

M. Dahlem

CSIRO/ATNF, Paul Wild Observatory, Locked Bag 194, Narrabri NSW 2390, Australia
e-mail: Michael.Dahlem@csiro.au

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Abstract. Australia Telescope Compact Array multi-configuration mosaicing of the Grus quartet of galaxies reveals the presence of spectacular tidal structures. 2.1×10^9 $M_\odot$ of neutral atomic hydrogen (H I) gas, i.e. 11% of all H I in the group, are found to be dragged from NGC 7582 into intergalactic space. About 1.34×10^9 $M_\odot$ of H I gas are contained in a tidal tail emanating from the north-western disk of NGC 7582, with a projected length of about 85 kpc and width of up to 32 kpc and a relative velocity with respect to the centre of NGC 7582 of 130–140 km s^{-1}. 7.7×10^8 $M_\odot$ of H I reside in an intergalactic H I cloud 48 kpc West of NGC 7582, which might originate from the disk of NGC 7582 as well and has no optical counterpart in a red Digital Sky Survey (DSS) image. These observations prove that tidal stripping is occurring in the Grus quartet and that tidal features in compact groups can be potentially important contributors of metal-enriched matter to the intergalactic medium. The tidal features around NGC 7582 cover an area of about 2000 kpc^2, almost doubling the group's cross-section for Lyman-α absorption of light from background sources compared to the optical extent of the member galaxies.

Key words. ISM: general – galaxies: ISM – galaxies: evolution – galaxies: halos – galaxies: starburst – galaxies: kinematics and dynamics

1. Introduction

Compact groups of galaxies are first-class laboratories for studies of galaxy interactions and their products. H I gas being more extended than the optical disk of many galaxies (e.g. Broeils & Rhee 1997) and its outer parts thereby being less tightly bound to the galaxy potential than other constituents, it is usually the first part of galaxies to react to tidal disturbances. Numerous examples have proven the diagnostic power of H I imaging spectroscopy in establishing how galaxy interactions work. Early numerical work by Toomre & Toomre (1972) was corroborated by H I observations of systems such as the Leo Triplet of galaxies (Haynes et al. 1979) and the NGC 4631 group (Weliachew et al. 1978), which was modeled numerically by Combes (1978). In the meantime, improved observations of the above systems were performed and similar features also detected in the NGC 4666 group (Walter et al. 2004), Stefan's quintet (Williams et al. 2002), the M 81/M 82 group (Yun et al. 1994) and other groups.

Tidal interactions of galaxies in groups are one of the dominating mechanisms by which metal-enriched gas from the galaxy disks can be transported into intergalactic space. This makes debris from galaxy interactions in compact groups, which can lead to mergers, a potentially important contributor to the metal enrichment of the intergalactic medium (IGM) at the present time, and also in the earlier, higher-density Universe (e.g. Gnedin 1998).

At the same time, tidal features significantly increase the cross-section of nearby compact groups to radiation from the early Universe compared to the optical extent of the member galaxies, making them potentially important low-redshift Lyman absorption systems. We do not have the sensitivity to detect low surface brightness H I emission beyond the local Universe yet. Only absorption line studies tell us that metal-enriched gas must be present at large distances (up to a few hundred kpc) from galaxies at intermediate redshifts. Nearby compact groups might constitute current-time counterparts of such systems, where we can study the intergalactic gas also in emission.

Australia Telescope Compact Array (ATCA[1]) observations of one such nearby group with extended tidal features, the Grus quartet, a southern spiral-dominated compact group of galaxies, are presented here. Section 2 describes the observations and data reduction. The results are presented in Sect. 3, followed by a discussion in Sect. 4.

2. Observations and data reduction

H I line observations of the Grus quartet were conducted with the ATCA over the course of more than 10 years. We present here a combination of all public data, obtained in compatible observing modes in the EW375, 750D, 1.5A, 6A and 6C

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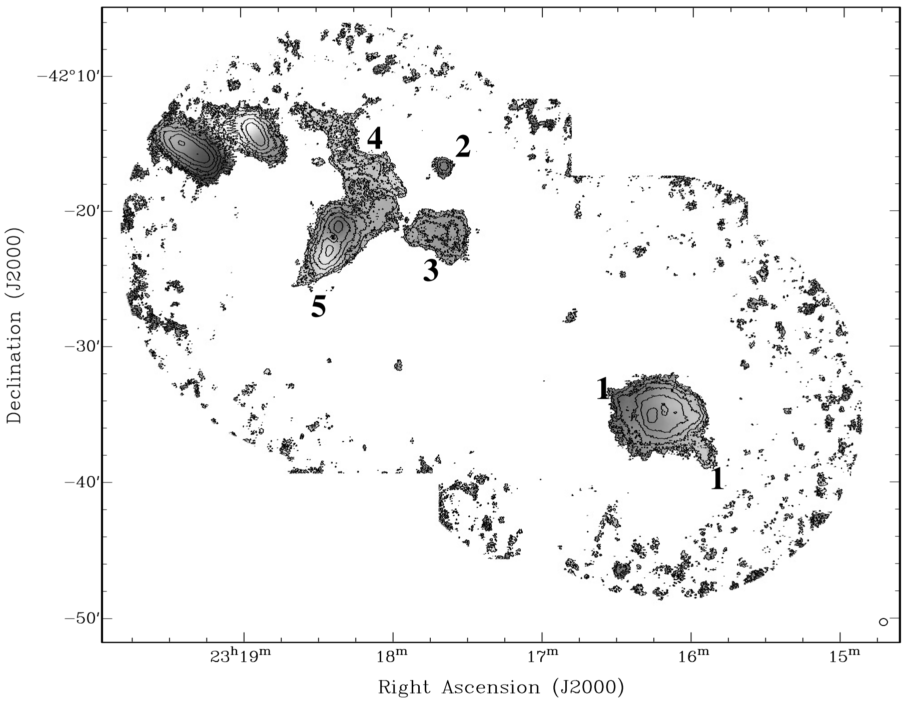

Fig. 1. HI velocity field of the Grus quartet (grey scale ranging from 1280 km s^{-1} (white) to 1850 km s^{-1} (dark grey)). Contours mark column densities of 5.5, 7.8, 11, ..., 352×10^{19} cm^{-2}. The major galaxies in this group are NGC 7552 (SW centre), NGC 7582 (NE centre) with associated tidal features, NGC 7590 (NE) and NGC 7599 (far NE). The beam is 34.″1 × 30.″6 (see lower right).

configurations, to study with high sensitivity the neutral atomic gas in this group. The total on-source integration time is 109.7 h, of which 43 h were spent on NGC 7552, 46 h on NGC 7582 and about 21 h on a position between these two galaxies.

1934-638 was used as the primary flux and bandpass calibrator, 2259-375 and 2311-452 as phase calibrators. The adopted flux density of 1934-638 is 14.94 Jy at 1.43 GHz. The data reduction was performed in a standard fashion, using the software package MIRIAD (cf. MIRIAD User's Guide), and the underlying radio continuum subtracted from the H I line data in the *uv*-plane.

Since data with different pointing centres were used, a mosaic image was produced. In this process a primary beam correction is applied automatically in MIRIAD (in the cleaning task mossdi). The original channel width of the data is 3.3 km s^{-1}; in order to further improve the signal-to-noise of the data, this was reduced offline to 13.2 km s^{-1}. The combination of several ATCA configurations leads to good *uv*-coverage, which provides good sensitivity to a wide range of angular scales, including very extended, faint emission. Results obtained with re-weighted data (robust = 0.5 weighting) are presented here, with a reduced angular resolution of 34.″1 × 30.″6, but at the same time increased sensitivity to extended emission compared to a high angular resolution (uniform-weighting) dataset.

3. Results

Figure 1 shows the H I velocity field of the Grus group, with total intensity contours superimposed. Several H I structures were found in the Grus quartet, in addition to the four primary member galaxies (see labels in the figures):

1. Weak tidal features on opposite sides of NGC 7552 (on a line towards the other members of the Grus quartet);
2. the dwarf galaxy LCRS B231454.2-423320, near α, δ(2000) = 23:17:38.9, −42:16:56;
3. an H I gas cloud with a central coordinate near α, δ(2000) = 23:17:40.7, −42:21:51 and a systematic velocity gradient from East (near NGC 7582) to West;
4. an H I tidal tail emanating from NGC 7582 towards North, with a projected length of 10′ (64 kpc), that almost connects with the gaseous disk of NGC 7590;
5. a faint tidal tail at the South end of NGC 7582, opposite the tidal tail described above.

The nuclear regions of both NGC 7552 and NGC 7582 are strong radio continuum sources at 1.4 GHz, against which H I gas is seen in absorption; thus the central minima in their H I distributions in Figs. 1 and 2. Based on an antenna temperature, T_b, to flux density (S) conversion ratio of 1.72 Jy/K and the relationship $N(\mathrm{H\,I}) = 1.8224 \times 10^{18}\ T_b$, the measured H I line flux densities were converted into column densities, see labels of Fig. 1.

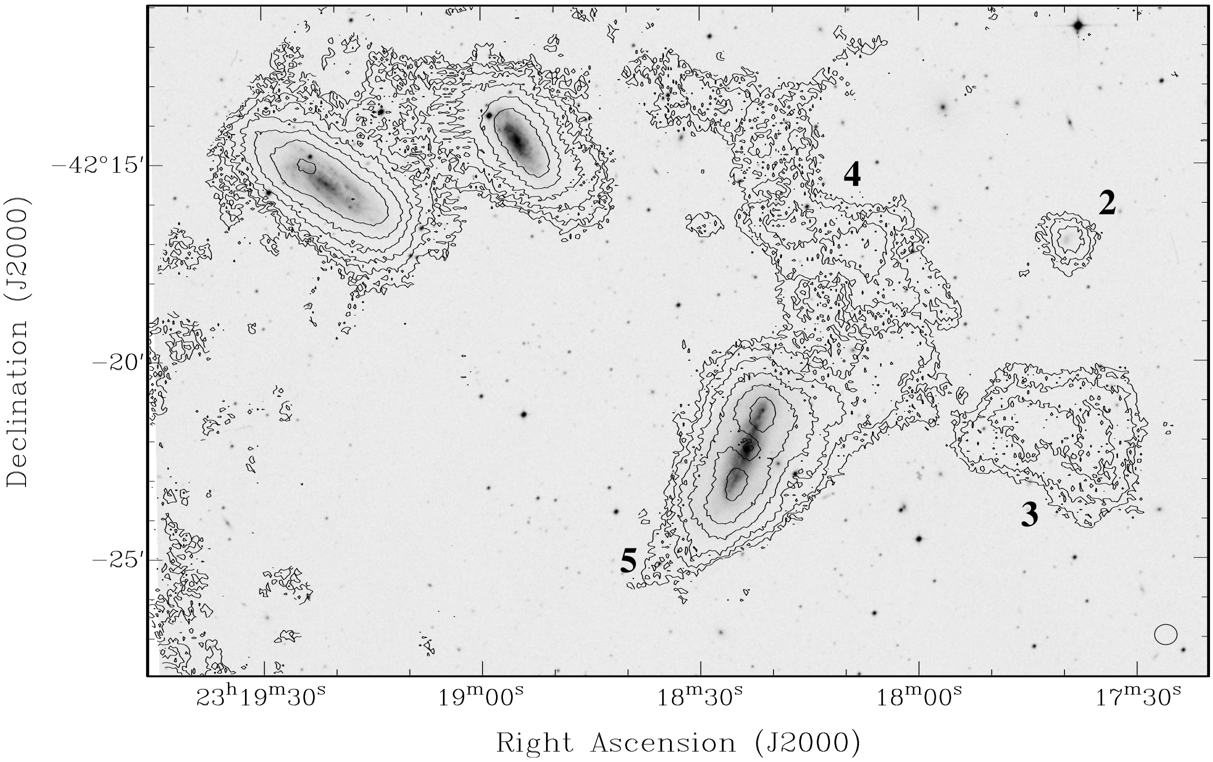

Fig. 2. The region around NGC 7582, with its abundant intergalactic HI features, displayed in more detail than in Fig. 1.

The noise near the edges of the mosaic is an artefact of re-weighting the data in the primary beam correction, which can be disregarded. Except near NGC 7599 (on the north-eastern edge of the field-of-view), this increased noise has no effect on the results presented here. Areas in the total H I image where the noise level exceeds 1.5 times that at the centre of the field-of-view were masked.

4. Discussion

4.1. Total HI gas mass

H I gas masses can be calculated from the observed total line flux densities, $f_{\rm HI}$, using the relationship

$$M_{\rm HI} = 2.356 \times 10^5\, D^2\, f_{\rm HI}\ [M_\odot]. \tag{1}$$

Values for the major galaxies in the Grus group are listed in Table 1[2]. The dwarf galaxy LCRS B231454.2-423320 has an H I gas mass of $9 \times 10^7\ M_\odot$. The total H I gas mass of the newly detected tidal tail of NGC 7582 is about $1.34 \times 10^9\ M_\odot$, that of the gas cloud West of NGC 7582 is $7.7 \times 10^8\ M_\odot$. f(H I) for NGC 7552 and NGC 7582 is underestimated due to the absorption seen against the nuclear continuum emission. However, this should not amount to more than about a few per cent of the total H I mass, because only a very small volume is affected. Uncertainties in the H I gas mass measurements are of order 10–20%.

[2] We adopt a distance of $D = 22$ Mpc, based on $H_0 = 75\ {\rm km\,s^{-1}\,Mpc^{-1}}$ and a virgocentric infall velocity of $300\ {\rm km\,s^{-1}}$.

4.2. Gas-to-total mass ratio

Based on the relation

$$M_{\rm tot} = 2.31 \times 10^5\, R_{\rm max}\, (v^{\rm i}_{\rm max})^2\ [M_\odot], \tag{2}$$

where $v^{\rm i}_{\rm max}$ is the inclination-corrected maximum rotation velocity and $R_{\rm max}$ is the radius at which $v^{\rm i}_{\rm max}$ is measured, we estimate the virial masses of the member galaxies in the Grus group (Table 1). Due to the disturbances of the galaxies and associated difficulties in unambiguously fitting the inclination angle, i, and $R_{\rm max}$, the $M_{\rm tot}$ values are typically accurate to within a factor of 2 only (not including uncertainties in the adopted distance, D). Keeping in mind these uncertainties, NGC 7582 is the only galaxy in the Grus quartet that appears to be H I-deficient compared to the other members. Its $M_{\rm HI}/M_{\rm tot}$ ratio is near the 25% value for Sab/Sb galaxies as derived by Roberts & Haynes (1994), while for their given Hubble types the three other galaxies in the quartet all have $M_{\rm HI}/M_{\rm tot}$ ratios near the expected median values. However, adding up the H I gas found in NGC 7582, plus that of the tidal tail and the western H I gas cloud (see Sect. 4.3), the H I-to-total mass ratio increases to 0.053, thus remedying this apparent deficiency. This is an indication of how significantly tidal interactions can influence gas-to-total mass ratios of galaxies (see also Verdes-Montenegro et al. 2001).

4.3. Tidal structures

The tidal H I structures around NGC 7582 are enormous in size and well-resolved by the ATCA. The northern tail (No. 4) is extraordinarily long (85 kpc; i.e. 1.5 times the length of the

Table 1. HI vs. total galaxy mass in Grus quartet galaxies.

Galaxy name	Hubble type (NED)	$f_{\rm HI}$ (Jy km s^{-1})	$M_{\rm HI}$ (10^9 $M_\odot$)	i (°)	$v^{\rm i}_{\rm max}$ (km s^{-1})	$R_{\rm max}$ (kpc)	$M_{\rm tot}$ (10^{11} $M_\odot$)	$M_{\rm HI}/M_{\rm tot}$
NGC 7552	(R')SB(s)ab;HII Liner	47.74	5.44	46	190	12.8	1.07	0.051
NGC 7582	(R'$_1$)SB(s)ab Sy2	29.13	3.32	64	226	7.5	0.88	0.038
NGC 7590	S(r?)bc	25.67	2.93	68	199	4.3	0.39	0.075
NGC 7599	SB(s)c	44.10	5.03	72	162	9.1	0.55	0.091

Magellanic stream) and, with a projected width of up to 32 kpc, as wide as a typical galaxy disk. Its velocities link up to those in the disk of NGC 7582, making it likely that it originates from the galaxy's gas disk. The maximum projected distance from the centre of NGC 7582 is 64 kpc, with relative velocities of up to 130–140 km s^{-1}.

The cloud West of NGC 7582 (No. 3) has no visible optical counterpart in the red DSS-2 image, down to a surface brightness level of about 22.0 mag arcsec^2, while the dwarf galaxy (No. 2) was detected at this level. This suggests that the interactions in the Grus quartet have led to the creation of an intergalactic gas cloud. Its projected distance from NGC 7582 is 7.′5 (48 kpc). Its size in our imagery is about 4.′2×3.′2 (27 × 20 kpc), which is comparable to the size of the H I disk in NGC 7590 (Figs. 1 and 2).

At the very faintest levels, within the noise of the data (and therefore not displayed here), there is an indication of a bridge connecting the western H I gas cloud with the base of the tidal tail where it roots in the disk of NGC 7582. Also the velocity continuity of both the western H I gas cloud's and the tidal tail's motion compared to NGC 7582 (Fig. 1) suggests that both have likely originated in that galaxy. Their combined mass of 2.1×10^9 $M_\odot$ is significant, compared with the total H I gas masses of the galaxies in the group (Table 1). If indeed coming from NGC 7582, this suggests that it is stripped of 39% of its H I gas, i.e. 11% of all H I detected in the entire group.

The presence of these prominent tidal features suggests that the Grus quartet is a dynamically young system in "phase 2" of its evolution, as dubbed by Verdes-Montenegro et al. (2001; their Fig. 7). The fact that the group as a whole is not deficient in H I (the apparently missing gas from NGC 7582 being found in its tidal features) confirms this, indicating that there has been no phase transition yet of H I to H$^+$, as would be typical of phases 3 and 4 in this evolutionary scenario. An example of a group in which such a phase transition has happened is Stefan's quintet (HCG 92; Verdes-Montenegro et al. 2001).

Tidal forces in the Grus group of galaxies are efficient in dislocating gas from the member galaxies' disks probably because of the very small velocity differences along our line-of-sight, together with the compactness of the group, indicating that its members might undergo frequent encounters. The total velocity span is only ca. 570 km s^{-1}, from 1280 km s^{-1} (low-velocity side of NGC 7590) to 1850 km s^{-1} (high-velocity side of NGC 7599), which is smaller than the rotation amplitude of massive galaxies such as M 104 (v_{20} = 772 km s^{-1}; Richter & Huchtmeier 1987).

4.4. Low-redshift Lyman-α absorbers

With a combined projected surface area at a column density of 5.5×10^{19} cm^{-2} of ca. 2000 kpc^2 the tidal features almost double the geometrical size of the Grus group compared to the optical size of its member galaxies, which increases its cross section for absorption of background light from sources such as e.g. active galactic nuclei. With typical column densities of up to a few times 10^{20} cm^{-2}, the tidal structures in the Grus group are therefore potential Lyman-α absorbers at near-0 redshift. As indicated above, this places the Grus group in one league with other compact groups exhibiting previously unknown extended tidal features, suggesting that the local Universe might be more opaque than previously estimated, especially if there is dust associated with the intergalactic H I.

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