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Ram Pressure and Anomalous Shell Formation in HoII

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Abstract. Neutral hydrogen VLA D-array observations of the dwarf irregular galaxy HoII, a prototype galaxy for studies of shell formation, are presented. The large-scale H I morphology is reminiscent of ram pressure and is unlikely caused by interactions. A case is made for intragroup gas in poor and compact groups like the M81 group, to which HoII belongs. Numerous shortcomings of the supernova explosions and stellar winds scenario to create the shells in HoII are highlighted, and it is suggested that ram pressure may be able to reconcile the observations available.

1. Introduction

HoII is a dwarf irregular galaxy on the outskirts of the M81 group, at a distance of 3.2 Mpc (M_B=$-$17.0 mag). It is one of the first galaxies outside the Local Group where the effects of sequential star formation on the interstellar medium (ISM) were investigated. Puche et al. (1992; hereafter PWBR92) present high-resolution multi-configuration VLA H I observations, revealing a complex pattern of interconnected shells and holes. They argue for self-propagating star formation, whereby supernova explosions (SNe) and stellar winds shape the ISM. While we do not wish to challenge the general relevance of such scenarios here, we will highlight numerous problems they face in the particular case of HoII. Some have been noted before, but others are mentioned for the first time.

We reanalyzed PWBR92's H I observations of HoII, keeping only the D-array data. We produced a continuum-subtracted naturally-weighted cube cleaned to a depth of 1σ (2.75 mJy beam^{-1}) and associated moment maps. The total H I map is shown in Figure 1 superposed on an optical image. A previously undetected, large but faint component extends over the entire northwest half of the galaxy, encompassing the H I cloud detected by PWBR92. The H I on the southeast side is compressed, giving rise to a striking NW-SE asymmetry, suggesting that HoII is affected by ram pressure from an intragroup medium (IGM). The velocity field shows a clear differentially rotating disk pattern in the inner 7–8$'$, but the kinematics at larger radii is rather disturbed. The total H I flux $F_{\rm HI} = 267$ Jy km s^{-1}, corresponding to 6.44×10^8 M$_\odot$.

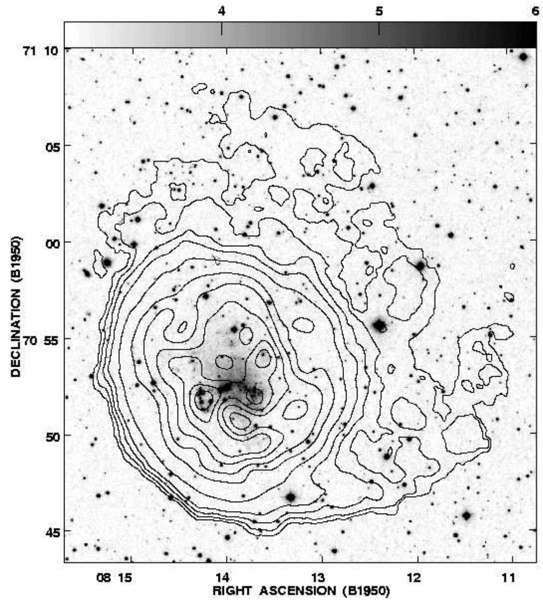

Figure 1. Total H I map of HoII from the VLA D-array data, superposed on a DSS image. Contours are 0.005, 0.015, 0.03, 0.05, 0.10, 0.20, 0.30, 0.45, 0.60, 0.75, and 0.90 times the peak flux of 8.5 Jy beam^{-1} km s^{-1} (2.10×10^{21} atoms cm^{-2} or 16.8 M$_{\odot}$ pc^{-2}). The beam is $66.''7 \times 66.''7$. The NW-SE asymmetry is obvious.

2. The Environment of HoII

The H I morphology in Figure 1 is reminiscent of ram pressure but could also be due to interactions. HoII is 475 kpc in projection from the M81 group center. At the (deprojected) group velocity dispersion of 190 km s^{-1} (Huchra & Geller 1982), it would take HoII a fifth of a Hubble time to reach the center of the group. HoII appears to be part of a subsystem of three dwarf irregular galaxies, with Kar52 (M81dwA) and UGC4483. If HoII is interacting, it must be with one of these. Kar52 and UGC4483 are much smaller and fainter than HoII and have irregular optical morphologies, but neither shows obvious signs of interactions (Bremnes, Binggeli, & Prugniel 1998). In H I, Kar52 displays an incomplete lumpy ring with little rotation (Sargent, Sancisi, & Lo 1983), and UGC4483 shows a peaked distribution with a faint envelope extending NW-SE (van Zee, Skillman, & Salzer 1998). The distance to HoII is identical to that of UGC4483 but also to that of NGC2403 and DDO44 to the SW, suggesting that HoII belongs to the NGC2403 subgroup, along with Kar52, UGC4483, NGC2365, and DDO44. Karachentsev et al. (2000) suggest that the NGC2403 subgroup is moving towards the M81 group at a velocity of 110-160 km s^{-1}. The environment of HoII thus does not support interactions as a likely mechanism to shape its large-scale structure, but rather suggests that it could have a large velocity relative to a putative IGM. Ram pressure must therefore be considered seriously to explain its H I morphology. H I observations of the entire region around HoII, Kar52, and UGC4483 should help clarify this issue and are underway.

3. IGM and X-Rays in Small Groups

The condition for ram pressure stripping can be written as

$$\rho_{\rm IGM} v^2 > 2\pi G \Sigma_{tot} \Sigma_g \qquad (1)$$

(Gunn & Gott 1972), where $\rho_{\rm IGM}$ is the IGM density, v the relative velocity of the galaxy with respect to the IGM, and Σ_{tot} and Σ_g the total and ISM surface densities, respectively. Taking $v \approx \sqrt{3}\sigma \approx 190$ km s^{-1} and Σ_{tot} and Σ_g (corrected for other gaseous species) at the first significantly disturbed contour in Figure 1, we derive a critical density for stripping $\rho_{\rm IGM} \gtrsim 4.0 \times 10^{-6}$ atoms cm^{-3}.

A virial mass of 1.13×10^{12} M$_\odot$ is derived from the main members of the M81 group (Huchra & Geller 1982). Spreading 1% of this mass in a sphere just enclosing HoII, we obtain a mean density of 1.4×10^{-6} atoms cm^{-3}, three times less than that required for stripping. This number provides a benchmark with which to compare more realistic calculations. The IGM will be more concentrated and clumpy, and the encounter may not be exactly "face-on", but since the group velocity dispersion is based only on the largest galaxies, it is probably underestimated, and the group is in any case unlikely to be virialized at the distance of HoII, making its velocity highly unconstrained. If HoII is bound to the M81 group, then the virial mass adopted is also severely underestimated. All these factors can easily bring the required and derived IGM densities in agreement. Typical parameters for poor groups are $R_{vir} \sim 0.5h^{-1}$ Mpc and $M_{vir} \sim 0.5 - 1 \times 10^{14} h^{-1}$ M$_\odot$ (Zabludoff & Mulchaey 1998), of which only 10–20% is in individual galaxies, leading to a mean density for the remaining matter of $\sim 4 \times 10^{-3}$ atoms cm^{-3} within R_{vir}. If only 0.1% of this is ordinary interacting baryonic matter, then its density is sufficient to strip the outer ISM of galaxies like HoII. This is promising since on scales of the virial radius, the dominant baryonic component in groups is the IGM. Zabludoff & Mulchaey (1998) report X-ray gas masses of $1 \times 10^{12} h^{-5/2}$ M$_\odot$ for their groups, leading to mean densities for the hot gas of $\sim 9 \times 10^{-5}$ atoms cm^{-3} within R_{vir}.

The total X-ray luminosity of groups does not correlate with the number of galaxies or optical luminosity, but it does with the velocity dispersion and gas temperature. A fit to cluster and compact groups yields, for $\sigma = 110 \pm 10$ km s^{-1}, $L_X = 10^{39.6\pm1.7}$ erg s^{-1} and $T_{\rm IGM} = 10^{-0.91\pm0.13}$ keV (Ponman et al. 1996). The correlation for loose groups alone yields $L_X = 10^{40.5\pm3.6}$ erg s^{-1} and $T_{\rm IGM} = 10^{-0.48\pm0.10}$ keV (Helsdon & Ponman 2000). The large errors are probably related to the wind injection histories of the groups, which in turn lead to shallow surface brightness profiles. There are also indications that the groups and clusters correlations are different, so both L_X and $T_{\rm IGM}$ are probably underestimates, and there can be a large amount of hot gas in M81-like groups.

Following Cowie & McKee (1977), the evaporation timescale for a typical cloud ($n \approx 1$ cm^{-3}, $R \approx 10$ pc) embedded in an IGM at the aforementioned temperatures is 6.2×10^5 to 2.8×10^7 yr. The H I "tail" in HoII extends over $7 - 8'$ in the radial direction. At 190 km s^{-1}, it takes HoII 3.6×10^7 yr to cross that distance. Given the strong dependence of the evaporation on the assumed properties of the clouds and IGM, the timescales calculated seem consistent with observations. In the conditions of interest here, cooling and viscous stripping (Nulsen 1982) are negligible compared to evaporation.

4. The Creation of Shells and Supershells

PWBR92 studied over 50 H I holes in HoII and argued for their formation through SNe and stellar winds. However, Hα and far-UV emission do not preferentially fill small holes or trace the edges of large ones. The shells are also devoid of hot gas, and X-ray emission is not preferentially associated with H II regions or H I holes (Kerp & Walter 2001). The SN rates derived from radio continuum observations and the H I shells agree (Tongue & Westpfahl 1995), but the energy is deposited in the central regions of HoII only, hardly helping to explain the formation of the outer shells. Furthermore, when useful limits are derived, most stellar clusters expected from massive star formation are not seen (Rhode et al. 1999). Multi-wavelength observations thus pose a challenge to SNe and stellar winds scenarios for the formation of the shells in HoII, particularly in the outer parts of the disk, where no star formation is expected or taking place.

Rhode et al. (1999) discuss other mechanisms for the formation of the shells. SN are most likely not spherically expanding in a uniform ISM, as assumed, the initial mass function could be very top-heavy, and gamma-ray bursts could also create holes, but all these mechanisms still require massive star formation in the outer parts of the disk. A fractal H I, overpressured H II regions, external ionization sources, and/or high-velocity clouds can bypass this requirement.

We suggest here that ram pressure provides another solution to the shell formation problem in HoII. Ram pressure can create holes in an H I disk where local minima in the surface density exist. It provides a mechanism to enlarge pre-existing holes, created by SNe or otherwise, and can explain the large energy requirements (or lack of observational signature) from SNe and stellar winds. Of course, ram pressure-driven shell formation should be properly modeled before making further claims. It should be easily distinguished from internal, pressure-driven events, as the shells will have a "bullet-hole" geometry like that caused by high-velocity clouds. In HoII's case, a direct proof of a dense IGM must also be found before any ram pressure model can be taken seriously.

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