Mapping the Hidden Universe: The Universe Behind the Milky Way – The Universe in H I
ASP Conference Series, Vol. 218, 2000
R.C. Kraan-Korteweg, P.A. Henning, and H. Andernach, eds.

Small Galaxies Blowing Big Bubbles

Jürgen Ott

Radioastronomisches Institut der Universität Bonn, Auf dem Hügel 71,
53121 Bonn, Germany

Fabian Walter

California Institute of Technology, Astronomy Department 105-24,
Pasadena, CA 91125, USA

Elias Brinks

Depto. de Astronomía, Universidad de Guanajuato, Apdo. Postal 144,
Guanajuato, GTO 36000, Mexico

Uli Klein

Radioastronomisches Institut der Universität Bonn, Auf dem Hügel 71,
53121 Bonn, Germany

Abstract. Some of the lowest-mass dwarf irregular galaxies, such as Leo A, Sag DIG and Cas 1, show a characteristic distribution of their neutral interstellar medium (ISM) as observed in the 21 cm line of neutral hydrogen (H I): the majority of the gas is found to be concentrated in a ring-like feature centred on, and embracing the optical counterparts of these objects. We present multi-array, high-resolution VLA H I and deep optical observations of Holmberg I and M81 dw A, both members of the M81 group of galaxies. Their H I is mainly stored at a galactocentric radius of about 0.8 kpc, at the edge of the optical images. The rings show neither expansion nor contraction.

If the neutral gas of Holmberg I was expelled by stellar winds and supernova explosions, resulting supposedly from a star formation event (or events) near the centre, the energy input is estimated to be $\sim 10^{53}$ erg. This translates to an upper limit for the age of this structure of $\sim 9 \times 10^7$ years. As the H I column density towards the centre is about one order of magnitude lower than in the ring, a "blow-out" scenario is likely; however, the fact that the ring seems stationary argues against "blow-away", in which case material would be completely returned to the intergalactic environment.

Optically, both galaxies fall clearly within the regime of low-surface brightness objects. Surface photometry based on Johnson $UBVRI$ band observations shows an attenuation of brightness inside the H I-ring relative to an exponential disk model which fits the outer parts well. Hα images of Holmberg I reveal a very low current star formation rate on the rim of the ring where H I column densities exceed $10^{21}\,\mathrm{cm}^{-2}$.

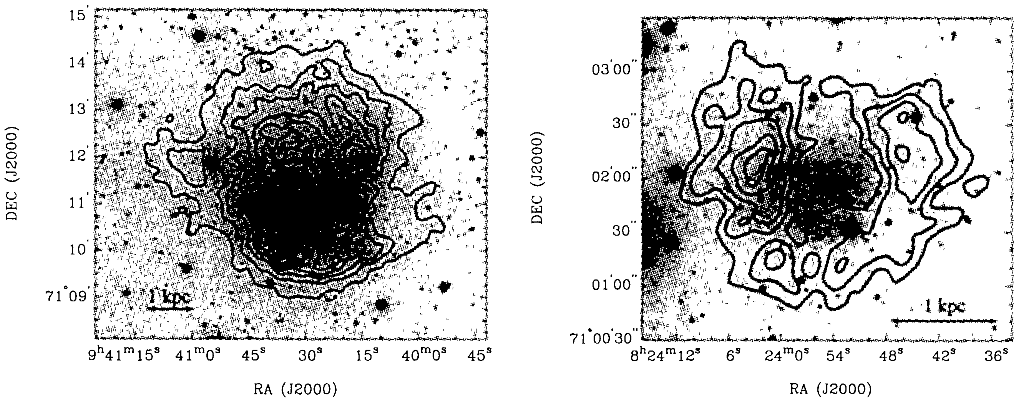

Figure 1. H I column density in the dIrrs Holmberg I (left, contours starting at $N_{\mathrm{H\,I}} = 1 \times 10^{20}\,\mathrm{cm}^{-2}$ in steps of $2 \times 10^{20}\,\mathrm{cm}^{-2}$) and M 81 dw A (right, contours starting at $N_{\mathrm{H\,I}} = 1 \times 10^{20}\,\mathrm{cm}^{-2}$ in steps of $0.5 \times 10^{20}\,\mathrm{cm}^{-2}$) each overlaid on a broad-band Johnson-Cousin R_c band image (at the distance of the M 81 group, 1′ corresponds to 1 kpc).

enriched ISM due to the energy feedback mechanisms mentioned above in low-mass dwarf galaxies (visible mass $< 10^8\,M_\odot$). As dIrrs form a numerous type of galaxy in the universe and are generally believed to be the building blocks of larger galaxies ("bottom-up" scenario) this may have implications for enriching the intergalactic medium (IGM) and the formation of galaxies at larger look-back times.

In this contribution, we present detailed observations of two galaxies at the lower-mass end of the galaxy luminosity function: Holmberg I and M 81 dw A. We use both high-resolution, multi-configuration archival data obtained with the NRAO[1] VLA (Very Large Array) in the 21-cm line of neutral hydrogen, and optical data in different broad- and narrow-band filters obtained at the Calar Alto[2] 2.2-m telescope.

2. H I Properties

Holmberg I and M 81 dw A, with total H I masses of $1.1 \times 10^8\,M_\odot$ and $8.4 \times 10^6\,M_\odot$, fall within the lower mass range of dIrrs. Both are members of the M 81 group of galaxies and we adopt for both objects the distance measurement as obtained by Freedman et al. (1994) for M 81 of 3.6 Mpc (m-M=27.80 mag). Their H I morphology is similar in terms of having a dominant ring-like structure centred on their optical counterpart (Fig. 1). It is striking that H I in the centre of the ring is virtually undetectable. Figure 2 shows the azimuthally averaged H I for comparison. In the case of Holmberg I about 75% of the total H I mass

---

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

[2] The Calar Alto Observatory is operated by the Max-Planck-Institut für Astronomie (Heidelberg) jointly with the Spanish Comisión Nacional de Astronomía.

1. Introduction

Observations in the 21 cm line of neutral hydrogen (H I) show that the interstellar medium (ISM) in our and in nearby gas-rich galaxies is dominated by bubbles, rings, worms, loops, arcs, and shells. Brand & Zealey (1975) introduced the term "cosmic bubble bath" to describe the topology observed, whereas others preferred the term "swiss cheese". In any case, we are obviously dealing with a "violent interstellar medium" (Tenorio-Tagle & Bodenheimer 1988). The standard model for the origin of these structures invokes star formation (SF) processes, especially those related to short lived, massive stars which are feeding back kinetic energy to the ISM via strong stellar winds and type II supernovae (SNe)(Tenorio-Tagle & Bodenheimer 1988; Oey & Clarke 1997 and references therein). However, alternative explanations might be required in some cases (see for example Rhode et al. 1999) such as the impact of high-velocity clouds, e.g. in the case of M 101 (van der Hulst 1988), and more recently the blasts of gamma ray bursts (Efremov, Elmegreen, & Hodge 1998; Loeb & Perna 1998).

Observationally, Heiles (1979; 1984) was the first to study the morphology and dynamics of a sample of bubbles and shells in the ISM of the Milky Way. This was followed by a similar study of the ISM in M 31 by Brinks & Bajaja (1986). They found structures covering the range of 100-700 pc in diameter (the lower limit set by the size of their beam).

In the standard picture, each SN releases 10^{51} erg of kinetic energy into its environment. As massive star formation tends to occur in complexes and associations, the SN explosions which will occur within a relatively short time span of 50 Myrs will all go off within a small volume, resulting in the deposition of $10^{52} - 10^{53}$ erg. The amount of energy deposited is to first order independent of morphological type of the host galaxy.

However, the effect on the ISM of the host depends on Hubble type, or rather galaxy mass. Since the gravitational potential in dwarf irregular galaxies (dIrr) is lower than in spiral galaxies, the ISM is less strongly bound to the disk. As a result, the gas disk puffs up leading to a smaller H I volume density in these systems as compared to grand-design spirals. Therefore, expanding shells can grow to larger dimensions before breaking out of the disk. Also, because dIrrs exhibit solid-body rotation there is a lack of shearing forces that distort features once they have formed. The combination of these properties results in larger shells in dIrrs, and longer lived ones, with diameters of up to two kpc as observed, e.g., in Holmberg II (Puche et al. 1992), IC 2574 (Walter & Brinks 1999), DDO 47 (Walter & Brinks 2000) and the Magellanic Clouds (Staveley-Smith et al. 1997; Kim et al. 1999).

We are now faced with the following question: if on the one hand the diameter of dIrrs decreases with lower mass, but on the other hand the size of the holes increases, what happens when the latter gets equal to or even larger than the former? Several low-mass dIrrs which seem to fall in this category are: Leo A (Young & Lo 1996), Sag DIG (Young & Lo 1997), M 81 dw A (Westpfahl & Puche 1993), Cas 1 (Huchtmeier priv. comm.), Sextans A (Skillman et al. 1988) and Holmberg I (Tully et al. 1978). They all share as a characteristic a big central H I hole.

Recent theoretical work by Mac Low & Ferrara (1999) and Ferrara & Tolstoy (2000) predicts the partial ("blow-out") or total ("blow-away") loss of the metal-

It is difficult to set constraints on the "blow-out" model since we have no knowledge of the H I distribution before the hole was formed. Extrapolation of a least-squares fit to the supposedly undisturbed H I profile beyond 130″ (see Fig. 2) yields an estimated mass loss of ~1/3 of the neutral material originally present. However, since we don't know the shape of the original H I distribution in this galaxy we cannot set a limit to the magnitude of a potential "blow-out".

3. Optical Properties

Holmberg I and M 81 dw A both belong to the class of low-surface brightness (LSB) galaxies. Their optical extent is similar to the size of the H I ring. However, the optical distribution in Holmberg I seems to be concentrated in two bright stellar features inside the H I ring, with a clear transition towards lower surface brightnesses right at the rim of the neutral gas. Stars that are bright in the U-band are found near the H I rim as well as in the centre of Holmberg I. Color magnitude diagrams indicate that the central stars are in the blue-loop phase and are therefore a somewhat older population. This finding seems to concur with a picture of propagating star formation, from the morphological centre outward, and hence supports the standard picture for the creation of huge H I cavities.

An analysis of the azimuthally averaged surface brightness shows for both galaxies a shallow slope for the exponential disk in the centre and a steeper one in the outer parts of the optical distribution. In the case of Holmberg I, the kink between these different components is at the same radius where the H I column density drops below $10^{21}\,\mathrm{cm}^{-2}$, the empirical threshold for star formation as discussed by Skillman (1987). This behaviour holds true for different colours.

4. Summary

The aftermath of star formation activity on the ISM of low-mass (dIrr) galaxies can be devastating. Most or all of the ISM can be blown out of the disk of the systems, temporarily changing their appearance dramatically. Moreover, this blow-out can have a profound influence on the star formation history, triggering secondary star formation in the shell of swept-up material or quenching SF altogether for long periods of time and making SF episodic.

Holmberg I and M81 dw A apparently both are in a post-starburst phase, with 75% of the ISM in Holmberg I and all the neutral gas in M81 dw A having been swept up in a huge ring of almost 2 kpc diameter. In the case of Holmberg I we derive an input energy of $\sim 10^{53}$ erg and estimate an age of $\sim$ 90 Myr. We find that current star formation, as evidenced by Hα emission, is taking place at those locations where the H I column densities exceed the magic threshold of $10^{21}\,\mathrm{cm}^{-2}$. The maps presented here and observations at other wavelengths, such as in the near infrared and at X-rays, are currently being analysed to try to obtain a more complete picture of these enigmatic objects.

Acknowledgments. We would like to thank B. Dirsch, T. Fritz, A. Weiss and U. Mebold for fruitful discussions. Without the funding of the Deutsche Forschungsgemeinschaft and the associated Graduiertenkolleg "Magellanic clouds

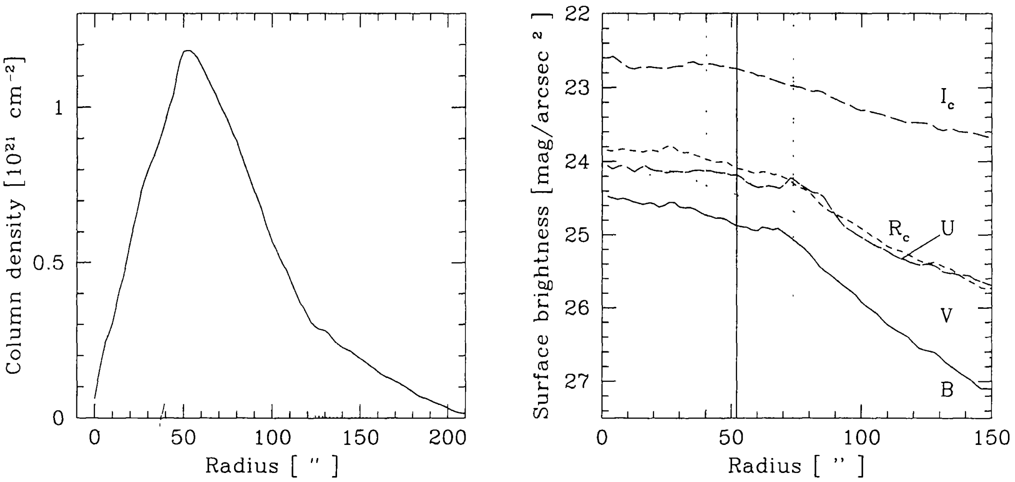

Figure 2. Left: Azimuthally averaged H I column density of Holmberg I (upper, solid line) and M 81 dwA (lower, dotted line), with the centre of the H I ring taken as origin. Right: Optical surface brightness profiles of Holmberg I. The solid vertical line shows the location of the peak of the H I column density as seen in the left graph, whereas the dotted lines mark the radii where the H I column density reaches $10^{21}\,\mathrm{cm}^{-2}$, the empirical star formation threshold.

resides in the ring, whereas in M 81 dw A all the neutral gas is stored in this morphological feature.

We performed a tilted-ring analysis on the velocity map of Holmberg I. Since this galaxy is seen nearly face-on we were only able to derive an upper limit for its inclination of $i < 12°$. The dynamical centre is some 0.75 kpc offset from the morphological (ring) centre. The H I velocity dispersions range from $\sim 9\,\mathrm{km\,s^{-1}}$ in the south to $\sim 12\,\mathrm{km\,s^{-1}}$ in the north-west, where we only see a faint underlying red stellar component. The offset of the dynamical from the morphological centre, as well as the distribution of the velocity dispersion, may indicate the existence of ram pressure effects, since the centre of the M 81 group, the M 81 triplet, is located to the south-east.

The scale height of Holmberg I ($\sim$ 600 pc) is comparable to that of other dwarf irregular galaxies and is therefore higher as compared to grand-design spirals in absolute and relative terms (eg. Puche et al. 1992; Walter & Brinks 1999).

We analysed Holmberg I in terms of the standard model, according to which the central star formation and subsequent energy release through SNe and stellar winds created the H I depletion. We find (applying the formula given by Chevalier 1974) an energy equivalent to the explosion of a few hundred SNe and an age of $\sim$ 80 - 90 Myr. After a similar time span, the ring will likely vanish due to the random motions (diffusion) of the neutral gas.

Note that the *big* H I ring is not the only cavity found in Holmberg I. Several smaller-scale features are suggestive of shells. However, the signal-to-noise and the velocity resolution in the H I data cube is too low to allow a proper analysis of these structures.