CHAPTER SIX

SUMMARY

The most exciting phrase to hear in science, the one that heralds new discoveries, is not ‘Eureka!’ but ‘That’s funny...’

— Isaac Asimov

During the course of this thesis a collection of archival datasets from the VLA at $\lambda$3 cm and $\lambda$6 cm and unpublished data from the WSRT at $\lambda$22 cm and $\lambda$92 cm was reduced to carry out a multi-frequency polarisation analysis of the starburst galaxy M82. In addition to that, a large amount of data was reduced at $\lambda$22 cm from recent observations of NGC891 and NGC4631 as well as WSRT data acquired with a successful proposal during this thesis at $\lambda$18 cm and $\lambda$22 cm from the interacting galaxy pair NGC672/IC1727. Apart from the M82 data at $\lambda$92 cm all data included full polarisation information allowing the derivation of Rotation Measures and regular magnetic field morphologies and strengths. Additionally, commissioning data from the LOFAR telescope of NGC891 and the MSSS project was used to examine the current capabilities of the LOFAR telescope and its data reduction and improve it.

Advanced data calibration techniques for radio continuum data are of utmost importance to achieve dynamic ranges sufficient for the scientific analysis of strong extended sources like M82, strong off-centre sources, which are more common at longer wavelengths, and/or large fields. With the newly proposed self-calibration technique in this thesis we were able to reach dynamic ranges of $\sim 50000$ for $\lambda$22 cm observations and even $\sim 10000$ for $\lambda$92 cm for the M82 data, which is by one magnitude better than standard calibration strategies. Additionally, the Peeling technique, which solves for the directional dependant corrections over the observed field for single sources, was successfully used to remove artefacts from off-centre sources in the WSRT-datasets from the three other fields improving the dynamic range significantly.

For the LOFAR observations with their large fields of view and high resolution nearly the whole sky is visible leading to sidelobes in the final images even from strong sources far away from the field. The demixing technique was successfully used to subtract the three well known sources, called the A-Team, from the data. For the first time simultaneous peeling of several sources was conducted on MSSS data successfully improving the dynamic range by an order of magnitude and reaching noise levels lower than the ones from the VLSS. This also included the
programming of a semi-automatic script to identify the strong sources in the field and calculate their appropriate fluxes for the calibration and subtraction.

The proper polarisation calibration especially in cases of strong sources is important to lower the instrumental leakage from the total power emission into the polarised signal. Therefore a channel-based calibration strategy was used for all datasets throughout this thesis. This procedure eliminated fluctuations caused by standing waves between the dish and secondary focus of radio interferometers helping to reduce the leakage by at least an order of magnitude.

The recently developed RM-Synthesis technique was used for the WSRT polarisation data at $\lambda 18$ cm and $\lambda 22$ cm. The classical approach for polarisation observations used data at two well separated wavelengths to determine the RM and magnetic field vector. The RM-Synthesis only needs an observation at one distinct wavelength and makes use of the rotation of the magnetic field vector over the observed bandwidth. Additionally, it solves for the $n \pi$-ambiguity and is much less affected by bandwidth depolarisation. This enabled the scientifically reliable usage of polarisation data at longer wavelengths.

The resulting high dynamic range data allowed us to look into the total power as well as polarised morphology of galaxy halos for all observed objects. For the case of the starburst galaxy M82 the extent of the halo at $\lambda 3$ cm and $\lambda 6$ cm is limited to the inner 1 kpc radius from the core, while a lot more diffuse emission up at $\lambda 22$ cm and $\lambda 92$ cm. A large difference in the extent of the northern and southern outflow is recognised. While the northern emission reaches up to 4-5 kpc into the halo, the southern one can only be traced up to 2.5 kpc. This asymmetry is also visible in the X-ray observations. A possible explanation would be a motion of M82 towards the group centre in the south causing ram pressure effects like in clusters of galaxies, but such an evolutionary scenario contradicts previous results. The northern outflow cone shows a lack of emission at long wavelengths in contrast to the two spurs surrounding it and steep spectral indices of up to $-2.5$ in its central part. This indicates that the dominant loss processes for the outflow cone in the north are either adiabatic or synchrotron losses. Numerical studies confirmed this in the case of NGC253, where a similar but not as well pronounced morphology was recognized.

A fitting to the scaleheights lead to very different results than in spiral galaxies. While for spiral galaxies typically a thin and a thick disk is found with scaleheights of 0.3 kpc and 1.8 kpc respectively, the values for M82 were lower by a factor of $\sim 3$. Additionally, an overall small gradient for the spectral index was found for the halo between $\lambda 22$ cm and $\lambda 92$ cm with $\alpha = -1.2 - -1.5$, while an increase is expected for galaxies where inverse Compton and synchrotron losses dominate the cosmic ray losses. Using an energy equipartition ansatz between the magnetic field energy and the cosmic ray particles results in an average field strength of 24 $\mu$G for the halo and 98 $\mu$G for the core region.

An integration over the emission of the core and the halo showed that free-free absorption is lowering the flux of the core at wavelengths from $\lambda 22$ cm on, while the halo emission is completely free of this feature at least up to $\lambda 92$ cm. This indicates a high contribution of ionisation losses in the core region. From a fit to the data of the core an average electron density of $19 \text{ cm}^{-3}$ could be obtained leading to a filling factor of $\sim 1.9\%$ for the ionised hydrogen. These fits are limited to just five datapoints and therefore have to be taken with care, but additional observations between $\lambda 22$ cm and $\lambda 92$ cm with the WSRT and even at lower wavelengths with
LOFAR will give better constrains on this.

A calculation of the loss timescales shows that at the current stage the ionisation and bremsstrahlung losses are dominating the expansion of the cosmic rays in the core region confirming the previous statement. Additionally, the recent $\gamma$-ray detections support the thesis of M82 encountering pion decay in the core region indicating very high particle densities, but lack the resolution to determine the exact origin of these particles within the galaxy.

To account for the above observations we pointed out a scenario where HII-regions and supernova remnants are dominating the radio flux in the core region. Cosmic rays are generated inside these small regions, where the medium is so dense that secondary electron production via pion decay is possible and cosmic ray electrons are suffering high losses due to magnetic fields. Using the same filling factor for the magnetic field as for the ionised medium, the magnetic field strength inside these compact regions was estimated to $5.16 \text{ mG}$. This makes synchrotron losses the dominant loss process inside these regions and the free path lengths for these particles at $\lambda < 6 \text{ cm}$ are smaller than size of these regions. This explains the difference of the extent of the synchrotron halo between frequencies of $\lambda 3 \text{ cm} / \lambda 6 \text{ cm}$ and $\lambda 22 \text{ cm} / \lambda 92 \text{ cm}$. Higher energetic particles lose their energy faster than lower energetic ones and are not propagated out into the halo. Since the pion decay mostly occurs inside these dense regions, it cannot help to produce electrons less affected by these high synchrotron losses.

In contrast to this heavier charged particles like protons or molecules are less affected by the magnetic field and therefore can escape these small regions more easily. The pressure to constrain these regions to sizes of several pc can be generated by the hard X-ray emission and the neutral hydrogen and molecular gas filling the whole core region of the galaxy. As soon as charged particles reach the lower density regions surrounding the star-forming regions they become coupled to the kinematic flow of the lower density X-ray gas and may leave the core region, which explains the similarity in the morphologies of H$\alpha$, PAH$^+$ and radio.

The loss timescale in the halo is of the same order as the escape timescale. Using a simple scenario, where cosmic rays are propagated from the core region into the halo results in free path lengths of only 990 pc, which is too low to build up a 4 kpc size halo. This gives evidence for a scenario where M82 experienced several starburst periods in the last 5–10 Myrs, in which the FIR- and radio-luminosity varied by one order of magnitude and it was possible to eject cosmic rays into the halo. The small gradient in the spectral index in the halo indicates that different propagation effects than in normal spiral galaxies are dominant. It cannot explain a halo where a continuous propagation of cosmic rays suffering from inverse Compton and synchrotron losses is fuelling the halo. Instead we propose that the synchrotron halo was produced by multiple ejections of cosmic rays and the observed spectrum is a superposition of several populations of those.

This scenario maybe completely different in normal star-forming spiral galaxies like NGC891 and NGC4631, where the star-formation is not as confined to the core of the galaxy as in M82, so that the distribution of the ionised gas and the magnetic field is more diffuse. The observed kiloparsec sized radio halos of these galaxies are most likely the result of an enduring star-formation over the whole disk and several hundred Myrs rather than short locally injected bursts triggered by an interaction lasting only several Myrs.

The overall influence of interactions on the radio continuum halo can therefore not be
neglected, but in how far the magnetic fields play an active role in the formation of halos is a matter of debate. As has been shown in this thesis, the magnetic field is completely coupled to the ionised medium in case of M82 and spurs in the halos of NGC891, NGC4631, and NGC672/IC1727 are accompanied by similar extensions in the neutral HI-morphology. Since HI-gas is always ionised by a small amount the magnetic fields can easily couple their motion to it. The magnetic field morphologies at the position of these features point away from the midplane of the galaxies with an increased fractional polarisation in all observed cases further indicating an increased ordering and/or stretching of the magnetic field lines by the outflows.

While the ratio between the regular and turbulent magnetic field strengths in typical spiral galaxies even in their spiral arms can be similar, the turbulent magnetic field in M82 is the dominant one. Therefore polarisation observations of M82 always suffer from a high fraction of Faraday dispersion. Even though a patch of polarised emission could be detected in the northern and southern halos at λ18 cm and λ22 cm and in the western disk at λ3 cm and λ6 cm. While the asymmetry in the disk can be explained by a bar pointing towards the observer on the western side and a depolarisation by the turbulent magnetic field on the eastern one, the observed origin of the poloidal halo field is explainable by a ring current in the molecular ring surrounding the centre of M82 with a radius of 115 pc.

This generation mechanism for a regular magnetic field is contrary to the one used for normal spiral galaxies. Here the αω-dynamo is one of the favoured explanations. While the regular disk field is generated by small scale fluctuations converting kinetic into magnetic energy, the observed X-shaped halo field is the result of this dynamo process in combination with an outflow scenario. In how far these outflows are cosmic ray driven or if they are coupled to the HI-gas, where a similar effect known as flaring is observed, is not known.