6

Conclusions and future research

In this thesis we have studied the properties of warps and searched for insights into how they could have formed. We have followed a two-pronged approach. On the one hand, we have used numerical N-body simulations to test the amplification of tidal perturbations by dark halos that could lead to the observed large amplitude warps. Second, we have used part of the Westerbork HI Survey of Spiral and Irregular Galaxies (WHISP) to characterize warps better.

6.1 Summary

In chapter 2 we have performed N-body simulations to test the amplification of the tidal field of a satellite galaxy by means of a dark halo. A calculation by Weinberg (1998) resulted in amplifications as high as 500% making the excitation of warps by satellites possible. Our simulations show that the halo does indeed amplify the effect of satellites but that the effect is much more modest, around 25%. We have made extensive checks including the use of different N-body codes and are confident that amplifications as high as 500% are very unlikely to occur.

While performing these N-body simulations we discovered that the line of nodes of the warp arising from a polar satellite was aligned with the orbit of the satellite. In chapter 3 we use a simple analytic model to calculate the line of nodes in such a system, and complement it with N-body simulations of a floppy disk. We have also explored the influence of non-circular satellite orbits.

On the second part of this thesis we have used data from WHISP to explore the warping of the HI disks of 26 edge-on galaxies. For each galaxy we have derived the center with a new method that uses kinematical and density information to minimize asymmetries. We have derived the rotation curves for our galaxies by performing edge-fits in the XV diagram to account for beam smearing and velocity resolution. We have derived the HI radial profile (and HI radius), warp radius and amplitude, and kinematical

and density lopsidedness.

We have detected warps in all the galaxies with HI layers more extended than the stellar disk. Their amplitude varies considerably from galaxy to galaxy and they are quite asymmetric (in shape and amplitude). The warping usually starts near the edge of the optical disk where the HI surface density drops down, which may indicate that warps occur in a region where the selfgravity of the disk is weak. We also found a dependence of warps on environment in the sense that galaxies in rich environments tend to have larger and more asymmetric warps than galaxies in poor environments. While this suggests that tidal interaction plays a role in warping, it seems likely that there are other effects at work that cause even quite isolated galaxies to warp. We also found that the presence of density lopsidedness (and in a weaker way that of kinematical lopsidedness) seems to be related to the presence of nearby companions.

6.2 Future work

Even if the work presented in this thesis has helped us to understand warps better, we still lack an understanding of how warps are created. There are several issues that need to be clarified if we want to get closer to the answer. The relationship of HI and optical warps is not clear, and deep optical photometry of warped galaxies is needed to understand the link between them. This kind of work would also be valuable to determine whether the extra gas that warped galaxies have at large radii was part of the galaxy and was warped later, or it is recent gas that is just falling with a different angular momentum than that of the inner disk.

The data presented in this thesis for the analysis of warps is a great improvement over previous samples in sensitivity and velocity resolution, but deeper HI observations would be of outermost importance to understand the kinematics of warps and to look for possible evidence of recent infall.

There are also indications that optical warps are significantly aligned in scales of several Mpc (Battaner *et al.*, 1991), which could mean that the environment plays a major role in the formation of warps (i.e. intergalactic accretion flows, intergalactic magnetic field). The improvement in sensitivity of the present radio telescopes have made possible to observe many galaxies in nearby clusters in the 21 cm line with good resolution (e.g. Ursa Major (Verheijen, 1997)) and it would be very interesting to see if HI warps are aligned as well. If this is the case we would have to look at larger scales than those of galactic instabilities for the answer to the warp phenomenon.