Dark matter and neutral hydrogen in spiral galaxies: The WHISP Program

Renzo Sancisi

The observations of the 21 cm emission line of neutral hydrogen with the Westerbork Synthesis Radio Tele-scope have provided crucial evidence on the presence of dark matter around spiral galaxies. They have also significantly contributed to the study of the dynamics, formation and evolution of disks and of the effects of the environment. WHISP (Westerbork HI Spiral galaxy Project) is the program designed to provide the observational data base for the extension of such studies to a large sample of spiral galaxies representative for the universe at low redshifts.

Spiral galaxies consist of a visible disk surrounded by a more massive and extended dark halo. This is the generally accepted picture, observationally supported by 21-cm line rotation curves. The Westerbork Synthesis Radio Telescope (WSRT) has played a central role in providing the basic radio data.

The method and the observational steps are well known. From the 21-cm line observations the density distribution of neutral hydrogen (HI) and the velocity field are obtained. From the latter, assuming that the gas moves in circular orbits, a rotation curve is derived. The standard procedure and analysis technique is illustrated in figure 1 for the spiral galaxy NGC 5204. Generally the HI extends, as in the case of NGC 5204, much beyond the optical boundaries of a spiral galaxy and the rotation curve can be traced very far out in radius, in the best cases up to 10 or more disk scalelengths. This is the greatest advantage of radio observations as compared to optical line observations.The measured rotation curve is compared with the rotation curve expected under the assumption that the distribution of the mass follows that of the light. In general, a large discrepancy is found between the two curves, particularly in the outer regions: the observed curve is approximately flat out to the outermost observed point whereas the curve expected from the visible disk has a, nearly keplerian, dropoff. This has led to the conclusion that the mass of a spiral galaxy is dominated by visible stars in the inner parts and by a massive dark halo in the outer parts (van Albada 1986).

The high quality, flat HI rotation curves now available for about 25 spiral galaxies give the most secure observational evidence for the presence of dark matter in the universe.

The study of dark matter in spiral galaxies is still going on at present. The difference between observed and predicted rotation curves and the derived discrepancy between the conventional dynamical mass and luminous mass of spiral galaxies is a firmly established observational fact. But various other old and new questions and issues are still open and a matter of dispute.

If one takes the conventional view that the masses of galaxies are dominated by dark halos the main questions arising are:

1 How massive and extended are such halos?
2 What is their density distribution?
3 What is the shape of dark halos? Are they spherical or flat?
4 What is the relationship between dark and luminous matter? Does it depend on luminosity, morphological type and environment?

The hope is that answers to such questions will help to understand how dark halos were formed in the first place and whether they are made of baryonic matter. Moreover, there is also the possibility that Newtonian mechanics or gravity may fail for scales of galaxies. Alternative interpretations to the dark halo hypothesis have been discussed (Sanders 1990) and, indeed, the modified Newtonian dynamics (MOND) has been shown to provide in general a satisfactory phenomenological description of the observed discrepancies.

Stars, gas and dark matter

In the standard picture a flat stellar disk and a more or less spherical halo conspire to produce, as a rule, a flat rotation curve. This suggests a tight coupling between dark and luminous matter. Over the years this has remained a major puzzle although the picture has somewhat evolved. It has been noticed that rotation curves are not featurless and not always perfectly flat. Their shape, i.e. the distribution of matter, has been found to depend on luminosity and morphology. The relative contribution of dark matter is much greater in low luminosity than in high luminosity galaxies. It has also been found that spirals with declining rotation curves outside the optical radius all have centrally con-densed light distributions. The shape of the mass distribution outside the optical radius is closely related to morphology and luminosity. This confirms that there exists a close link between the dark halos and the luminous parts of galaxies, as suggested originally, and seems to point to a baryonic nature of the dark halo matter.

Is there also a close coupling between dark material and neutral gas? There are two results which are suggestive in this respect. One is that in each individual galaxy the HI and dark matter components have very similar radial distributions, whereas the luminosity profile has a totally different shape. The other is that the relative total amounts of HI gas and of dark matter do not seem to depend on morphological type (Broeils 1992), whereas the masses of both HI and dark matter components increase significantly from early to late type galaxies. These results seem to suggest a close connection between the neutral gas and the dark material and point, perhaps, at a baryonic nature and flat distribution of the dark component.

Current and future work with the WSRT

The study of dark matter in spiral galaxies has occupied a prominent place in the 21-cm spectral line work with the WSRT. In this a number of PhD research projects, some of which supported by NFRA, have played a crucial focusing
role. After the pioneering studies of Bosma (1978) and Wevers (1984), the observational effort was pursued with increased sensitivity and more refined analysis techniques. Begeman (1987) derived high quality (Class I) rotation curves for a small sample of carefully selected spiral galaxies (e.g. NGC 3198) and established beyond any doubt the need for dark matter. Broeils (1992) extended the study to a larger sample of galaxies over a wide range of luminosities and morphological types and contributed decisive evidence showing that the relative amount of dark matter increases with decreasing luminosity and from early to late types.

At present Sicking is making a detailed investigation of a few selected spirals to determine the shape of the halos, Rhee is studying the Tully-Fisher luminosity-velocity width systematics for a large sample of galaxies and Verheijen is investigating the Tully-Fisher relation and the dark/luminous matter properties for a complete sample of spiral galaxies in the Ursa Major cluster. Parallel studies with the VLA in these recent years have brought important new information on a few late-type low-luminosity galaxies (e.g. DDO 154), on the extent of halos (NGC 3198) and on the systematics of rotation curves (e.g. declining curves).

All these various studies, based on a small number of carefully selected objects, had an exploratory character. It has become clear now that significant progress in our knowledge of dark matter in galaxies can be achieved only by a major effort with a drastic increase of the galaxy sample. A wide range in luminosities and morphological types must be covered. The construction of such a sample is the primary goal of the large Westerbork HI Spiral galaxy Project (WHISP) started by Van Albada and coworkers. The aim is to observe about 1000 of the brightest galaxies (blue diameter > 2 arcmin) at declinations higher than 20 degrees, and, so far, about 100 have been observed. For a success in this survey work the major instrumental requirement is sensitivity. It is essential that the system kinematics can be traced with high signal/noise as far out as possible in galactic radius. For the interpretation of rotation curves good photometry is also indispensable. The comparison of observed rotation curves with the expected rotation curves for the stellar disk has been the decisive method that has led to the conclusions about the discrepancy between dynamical and luminous mass. Multicolour CCD photometry is available

for a large number of galaxies or is being obtained in separate programs.

In addition to the main line of research on dark matter via the derivation of rotation curves, the WHISP data base is important for a number of other studies. Some of these are closely related, as they deal with the structure and kinematics of the HI layers. Others concern the interaction with the environment and bear on the formation and evolution of disks.

Structure and dynamics of disks: asymmetries, warps and HI halos

It has been clear from the early HI observations that large asymmetries in the HI distribution and kinematics exist in spiral galaxies, and recently it has been shown that they are not a few unusual exceptions but instead are quite common. One of the most striking examples is the lopsided HI picture of M101. Their high occurrence rate and the fact that they also seem to be present in the old stellar disks suggest that asymmetries are long lived. Furthermore, the HI density and velocity maps suggest that the lopsidedness is not a minor but a large-scale, structural distortion affecting the whole disk. It may have been imprinted at formation or result from interactions and accretion in the past. Whatever its origin and the history of the galaxy, it must now contain information on the mass distribu-tion and dynamics of the system and in particular on mass, shape and extent of dark halos. It is, therefore, important to study the phenomenon of lopsidedness on a large sample of objects and determine its systematic behaviour. In this respect it is also necessary to construct realistic models of non symmetric disks.

The detailed vertical distribution of neutral hydrogen in spiral galaxies is known only for a small number of objects. Warps in the outer parts of the HI layers seem to be the rule as they are seen in the HI density maps in most of the edge-on galaxies observed and are inferred from the velocity fields of less inclined systems. They still form an interesting puzzle.

The presence of HI gas in the halo region of galaxies has not been well studied yet, mainly because of insufficient sensitivity. The best case investigated in detail so far is that of NGC 891 which is nearby (~ 10 Mpc), is almost perfectly edge-on and is not significantly warped. The HI map of this galaxy (figure 2) shows a gas layer with extended, faint wings on both sides. The interpretation of these high latitude features is still uncertain and it is not at all clear that they are due to an outer flare of the HI layer as was proposed in earlier studies. Such observations are not only of great interest for the study of the gas in the halo but are also crucial for the determination of the vertical distribution of dark matter.

The effect of environment: interaction and accretion

From the HI line observations collected in the past 20 years with the WSRT and 10 years with the VLA for an increasing number of objects an "HI picture" of spiral galaxies is beginning to emerge. The density and velocity structures of HI allow us to distinguish between "internal" phenomena, related to processes in the disk (e.g. star formation) and "external" effects due to the interaction with the environment. A tentative classification based on HI morphology and kinematics can already be made. It has become clear in this way that a large number of systems are heavily disturbed by strong tidal interactions. Well-known examples are the Antennae, the M81-M82-NGC3077 and the NGC4656-NGC4631 groups. But also an increasingly larger number of systems are being found which are experiencing a softer kind of interaction with small companions or show peculiar structures which may be relics of such events in the recent past. These cases are about one quarter of the number of objects mapped in HI so far. They indicate that episodic accretion of gas in galaxies is indeed taking place even at present and suggest that such infall may be playing an important role in feeding the disk with fresh material from outside. The best examples of such events are those of M 101, NGC 628 and NGC 3359. Because the sample of spirals used for this study is affected by several biases and incompleteness, a better and more quantitative estimate of the frequency of infall events has so far not been possible. A large sample of spiral galaxies with HI maps, as WHISP will provide, is ideal for such a study.

Scientific outlook and cosmology

A number of spiral galaxies have been observed in the 21-cm HI line with the WSRT in the past twenty years. They have been selected for specific studies. These observa-tions have uncovered many new facts and have significantly contributed to our knowledge and understanding of galaxies. One of the main limitations has been the necessary restriction in this pioneering stage to a small sample of nearby galaxies, mainly for reasons of sensitivity. Reasons have been given above for a substantial increase of the number of objects with HI data and for the creation of a more representative sample. This has become possible now thanks to technological developments and improvements of receiver sensitivity in recent years.

There are now exciting developments in the study of sys-tems at large distances which also give a new perspective to the work which is going on for nearby objects. Detailed studies of the structure and dynamics of galaxies out to redshifts of 0.2 - 0.5 have become possible at optical and infrared wavelengths. The effects of evolution with time are being investigated. The presence of dark matter in such distant galaxies can be tested. These developments add interest, for an understanding of the observations of the systems at high redshift, to a substantial increase of the sample of objects nearer to us. In this view the creation of a representative "Shapley-Ames" sample of galaxies with detailed HI data, as envisaged by WHISP, is a necessary and urgent undertaking.