GAS AT LARGE RADII

R. Sancisi
Kapteyn Astronomical Institute
University of Groningen,
Groningen, the Netherlands

A considerable fraction of the neutral hydrogen in spiral galaxies is generally found at large radii and beyond the optical image. This outlying gas either forms an extension of the stellar disk and of the inner HI layer, or, is concentrated in a ring. It shows well ordered motion around the galaxy, although the plane of the orbits is generally inclined with respect to the inner disk. The study of this gas is important for at least three reasons: i) although it represents only a very small fraction of the total mass it can be used as a tracer of the kinematics to determine the total mass and the mass distribution of the system, ii) it contributes to the galactic cross-sections needed to explain QSO absorption lines, iii) its physical and chemical properties may throw some light on the formation of galactic disks and their evolution.

The general kinematical properties of the HI have already been reviewed by Bosma (this symposium). I will therefore discuss the main properties of the density distribution and add only a few comments on the rotation curves in the outermost regions of galaxies.

1. THE TOTAL RADIAL EXTENT

In the majority of isolated spiral galaxies, the neutral hydrogen is found to extend beyond the bright optical image, generally out to one or two Holmberg radii, at column densities of about 1×10^{20} atoms cm^{-2} (Bosma, 1981b). In a number of galaxies, such as Mkn 348, HI emission has been detected out to several Holmberg radii (cf. Sancisi, 1981), but these must probably be regarded as exceptional cases. In fact, observations of a dozen isolated galaxies down to column densities of about 2×10^{18} cm^{-2} (Briggs et al., 1980), indicate that the HI layer at such low density levels generally does not extend beyond 2-3 Holmberg radii. It is unlikely that in the near future significantly lower detection limits will be reached and that HI emission will be traced at levels much fainter than 1×10^{18} cm^{-2}. But, absorption spectra of faint QSO and background galaxies may provide a more sensitive test to the presence and extent of gas around galaxies.

E. Athanassoula (ed.), Internal Kinematics and Dynamics of Galaxies, 55–62.

2. Z-DISTRIBUTION

In the outer parts of galaxies, the HI layer generally exhibits large departures from the galactic plane. The bending is clearly visible in HI maps of galaxies seen edge-on or inferred from the kinematics of galaxies viewed more face-on. A comparison of HI and surface photometry maps shows that the bending of the gas layer generally begins almost exactly at the optical edge. This is clearly demonstrated in Fig. 1 where channel maps of HI are reproduced on the same scale as the "optical" map of NGC 5907. In this galaxy the stellar disk does not show any appreciable bending, whereas in NGC 4565 a slight warp is also noticeable in the optical disk (see Van der Kruit and Searle, 1981).

All galaxies viewed more face-on and with HI extending beyond the optical image show large-scale disturbances in their velocity fields which are usually considered to be the "signature" of a warp (cf. Rogstad et al., 1974). This effect is particularly strong in galaxies of very low inclination, as in NGC 628, recently studied by Briggs (1982) and by Van der Kruit and Shostak (1982, private communication).

All observations of warps show or suggest the integral sign shape seen in NGC 5907 (Fig. 1), but the two sides are generally not completely symmetrical in their radial extent, degree of warping, and position angle. NGC 4565 and our Galaxy are good examples of such asymmetries. In NGC 5907 and 4565 and in the southern side of our Galaxy, the warping does not continue to increase at large radii: the HI layer seems to settle to a new plane or perhaps turn back toward the principal plane. The outer HI layer of our Galaxy exhibits in addition to the warping, a "scalloping" up and down with respect to the galactic plane (Henderson et al., 1982; Blitz et al., 1982). Finally, in addition to these "smooth" warps, there are also the more discontinuous distributions found, for example, in NGC 4736 (Bosma et al., 1977), Mkn 348 (Heckman et al., 1982) and in some SO galaxies (Van Woerden, this symposium), where the outlying HI is concentrated in a ring tilted with respect to the inner disk.

The thickness of the HI layer is known to increase in the outer parts of our Galaxy (cf. Henderson et al., 1982) and of NGC 891 (Sancisi and Allen, 1979). But the actual z-structure is not known in detail, and may be less simple than the picture suggested by a one-component layer of increasing thickness.

3. RADIAL DISTRIBUTION

The detailed distribution of HI surface density is known for a number of spirals. For some, photometric data also exist and therefore can be compared with the luminosity profile. The systems are often lopsided (Athanassoula, 1979; Baldwin et al., 1980; Bosma, 1981b), however, and the radial profiles obtained by averaging over all azimuthal angles are unfortunately a poor representation of the actual distributions. The

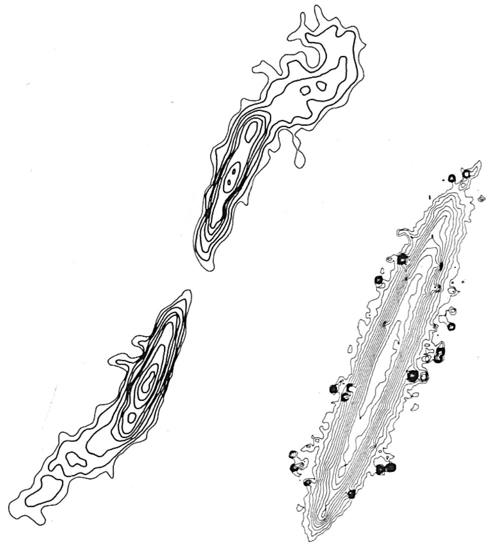

Figure 1. HI and optical pictures of NGC 5907 (on same scale, north at top). Left: map of HI emission at radial velocities 882 km/s (top) and 452 km/s (bottom). The contours are 2, 4, 8, 12, 16, 20, 28, 36 and 44 K. The FWHP beam is 25"× 30" (Sancisi, 1982; in preparation). Right: Isophote map of the surface brightness distribution (Van der Kruit, 1979). The contour interval is $0^{m}.5$ with the faintest contour at 27.5 J-mag arcsec^{-2}.

lopsidedness is not only present in the outer parts, but generally continues in the inner parts, where it is observed also in the distribution of the light and of the radio continuum emission. In the inner parts the displacement is often opposite to that of the outer parts, suggesting perhaps a one-arm spiral structure. Some substantial asymmetry is also present in the rotation curves.

Fig. 2 shows separately the projected HI density distribution along the northern and southern sides of NGC 891 major axis (Sancisi and Allen, 1982; in preparation). The flatness of the distribution in the inner region (R < 4') is partly due to the effect of large optical depth (cf. Sancisi and Allen, 1979). Also, a large fraction of the gas in this region may be in molecular form and therefore missing from the diagram. At the edge of the disk, the density has a steep drop-off followed at larger radii by a "shoulder" or "tail", which is more pronounced and extended on the southern than on the northern side. This shape, and in particular the "shoulder", seems to be a general characteristic of the radial density profiles of spiral galaxies. The shoulder may be more or less pronounced, but is found in the majority of galaxies which have extended HI layers, and usually starts near the Holmberg radius. Some striking examples of such distributions are shown in Fig. 3a. Other cases are those of NGC 2841 and 3198 (see Bosma, 1981a) and NGC 4565 (Sancisi, in preparation). The gas forming the shoulder is the same component which is generally warped (as in NGC 628), and is often asymmetrically distributed around the galaxy (as in NGC 891). The asymmetry suggests that this gas may be moving in off-set eccentric orbits instead of circular orbits. Also the HI rings found around some galaxies (e.g. Mkn 348) may represent extreme examples of such "shoulders". The radial and z-distributions observed in NGC 891 suggest that the shoulder gas may form an envelope (in all directions) surrounding the entire galaxy. The face-on column density in these shoulders is typically a factor five

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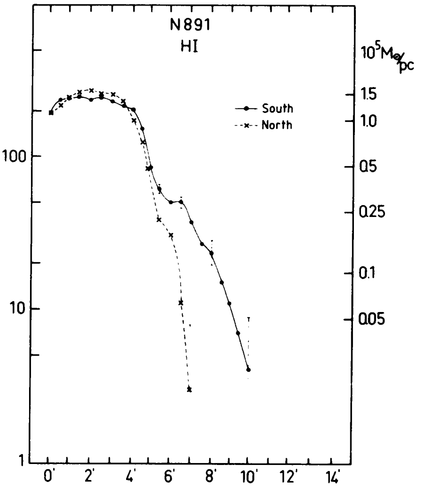

Figure 2: Northern and southern major axis profiles of the projected HI density in NGC 891, obtained by integrating the 21-cm line emission in velocity and in the direction perpendicular to the major axis (Sancisi and Allen, 1982; in preparation). The beamwidth along the major axis is 30". Note "shoulder" at 6-10 arcmin.

lower than in the peak of the inner disk. The amount of gas in the shoulder is of the order of 10 to 50% of the total galactic HI content.

The shape of the HI distribution and the origin of the shoulder may be related to the process of star formation, which causes depletion of the gas at smaller radii (cf. e.g. Fall and Efstathiou, 1980). Alternatively, there may be dynamical effects in the region where the shoulder begins, which cause the gas to move inward and/or outward.

In general the HI-to-luminosity ratio increases with radius, but the relative amount of HI and stellar mass at the edge of the disk seems to vary greatly from galaxy to galaxy. At the optical edge of NGC 891 less than 20% of the disk mass is in HI and more than 80% in stars. This is based on the luminosity model of Van der Kruit and Searle (1982), their assumption of $(M/L)_{old\ disk} = 7$, and the HI observations of Sancisi and Allen (1979). The opposite situation is found in NGC 5907, where at the optical edge most of the disk mass is in HI. The latter, in fact, seems to extend the exponential stellar disk beyond the optical cut-off radius. It is interesting to note in this regard that the stellar disk of this galaxy appears to have a large scalelength (5.7 kpc), but to cut-off at a remarkably small radius of only 3.4 scalelengths. This is about one scalelength less than found in most spirals of the sample of Van der Kruit and Searle (1982). It is conceivable that the unusually large warping of the outer HI layer observed in this galaxy (Fig. 1) may be related to these properties of the stellar and HI disk (i.e. large scalelength, small truncation radius, extended HI layer).

The amount and distribution of total ("dark") mass, as inferred from rotation curves, are so uncertain that a comparison with the HI is of little use. There is a suggestion, however, that in the outer parts of galaxies the HI and the "dark mass" may decrease similarly (see Bosma, 1981b) and may therefore be coextensive.

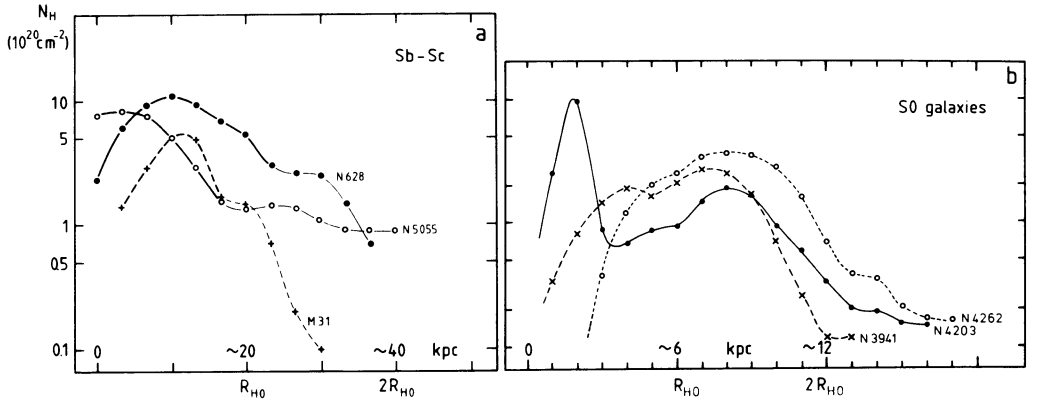

Figure 3. Radial distributions of averaged HI surface densities. a) Spiral galaxies NGC 628 (Van der Kruit and Shostak, 1982; private communication), NGC 5055 (Bosma, 1981a) and M 31 (cf. Sofue and Kato, 1981). b) SO galaxies observed at Westerbork by Van Driel, Van Woerden, Schwarz et al. (1982, private communication; Van Woerden, this symposium). R_{HO} is the Holmberg radius. Note the much larger approximate size (kpc) of the three spirals as compared to that of the three SO's.

4. DEPENDENCE ON MORPHOLOGICAL TYPE AND GROUP OR CLUSTER LOCATION

A clear and simple dependence of the total HI extent and of the shape of the HI distribution on the morphological type of the systems does not seem to exist. Extended HI disks are found around late-type spirals and irregular galaxies as well as around early type spirals and SO's. But it is possible now to compare the HI density distribution of spirals described above with that recently found in SO galaxies. For a dozen SO's recent Westerbork observations have shown that the gas is concentrated in rings surrounding the optical image of the galaxy (Van Woerden, this symposium). Fig. 3b shows the radial distributions of HI surface density for three SO galaxies normalized to the Holmberg size. The HI is concentrated in a broad component peaking slightly outside the Holmberg radius.

A comparison with the diagram of the Sb-Sc galaxies (Fig. 3a) shows that inside the Holmberg radius the HI in the SO's is deficient by a large factor, whereas the HI rings of the SO's have similar HI densities and similar locations with respect to the Holmberg radius as the "shoulder" of the Sb-Sc systems. If instead of referring to the photometric radius, the comparison is made between the HI densities at a given distance from the center, the HI appears to be deficient in both types of galaxies inside 6 kpc (i.e. in the bulge region) and the peak of the radial density distribution is between 5 and 12 kpc, with the density in the SO's down by a factor 4. The galaxies compared here, especially the

SO's, are too few and are not representative of their type. Therefore, no conclusions seem justifiable at this stage.

The HI distribution in the outer parts of a galaxy depends on its location in a group or cluster. HI tails and bridges can be traced to large distances from a galaxy when there is a strong tidal interaction with another galaxy or a group. The dependence of the HI distribution on the location in a cluster has been studied recently by Giovanardi et al. (1982) for the galaxies of the Virgo Cluster. These authors find that the hydrogen diameters, defined in terms of scalelength, are significantly smaller for galaxies in the core of the cluster than in the outer parts, and suggest that rampressure stripping of the outer galactic disks by intracluster gas and/or tidal disturbances may be the explanation. An obvious question, soon to be answered by higher angular resolution observations, is whether and how the shape of the radial density profile is affected, and whether for instance the "shoulder", described above, has vanished in the galaxies of the cluster core.

5. ROTATION CURVES

In order to obtain the mass distribution of galaxies and to establish or rule out the presence of massive halos, the kinematical properties of the gas at large radii must be accurately known. It has already been emphasized that the derivation of rotation curves in these outer regions is often complicated by geometrical effects, such as warping, and by large-scale non-circular motions, whose existence is suggested by the asymmetries in the HI density and velocity distributions. Yet the improved sensitivity and techniques of data analysis, and a better understanding of the physical properties of the outlying gas, should lead for at least a number of carefully selected objects to accurate values of the rotational velocities out to 1-2 Holmberg radii.

In all three edge-on galaxies studied in detail and reported above (NGC 891, 4565 and 5907), the rotation curves are approximately flat out to the optical edge found by Van der Kruit and Searle (1981). Beyond this radius, the maximum deviations of observed radial velocities from the systemic velocity, which usually give the rotational velocity, decrease by about 5 to 20%. At approximately the same radius, the properties of the gas change: the gas layer is warped and probably thicker, the density drops off and the "shoulder" begins. In NGC 891 there is no warp but the distribution becomes lopsided. It is therefore not clear that the deviation observed in the radial velocities means a declining rotation curve. The consequences of declining rotation curves on the disk halo masses of these galaxies have been explored in recent work by Casertano (1982, and this symposium) in a model for NGC 5907 and by Bahcall (1982), who estimates for NGC 891 in the case of a declining curve, a halo mass as low as 1-2 disk masses.

Also in other galaxies (e.g. M 31 and NGC 3198), a smooth decrease in the rotation curves takes place inside or near the edge of the optical disk (cf. Sofue and Kato, 1981; Bosma, 1981a), and in some systems (e.g. NGC 2841) a similar effect may be present but masked in the published curves by beam-smearing effects, which tend to cause an underestimate of the rotational velocities in the region of the optical disk. It should be emphasized, however, that this decrease is not in itself evidence against the hypothesis of massive halos. This will depend on whether the rotation curves continue to drop, as suggested by NGC 891, or remain approximately constant as they seem to be doing in M 31 and NGC 3198.

SUMMARY

The outlying gas of spiral galaxies seems to undergo a more or less abrupt change of its properties at some radius, a radius which is approximately at the Van der Kruit and Searle (1981) edge of the optical disk and generally close to the Holmberg radius. The main effects observed at approximately this same radius are the following:

1) The gas layer is warped and probably thicker.
2) The density profile shows a drop-off by a factor of five and a "shoulder" appears in the outer parts.
3) A decrease of radial velocity takes place, which may imply a drop-off in the rotation curve.

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DISCUSSION

INAGAKI: You mentioned that in some galaxies there is a bending in the optical picture. Do you think that the stellar disk of old stars is also bending? If only the stellar disk of young stars is bending, then this might be due to the bending of the HI.

SANCISI: The bending seen in the optical picture of NGC 4565 (Van der Kruit and Searle, 1981) and of other galaxies, such as NGC 3187, is most probably a bending of the old stellar disk.

BLITZ: Is it possible that the turnover in the warp that you see in some galaxies is related to the "scalloping" which has recently been detected in the Milky Way?

SANCISI: The turnover in the warp of NGC 5907 and NGC 4565, if it is indeed present, is of a larger scale than the "scalloping", and more similar to the turnover in the southern warp of our Galaxy. Effects such as corrugations or scalloping of the HI layer would be difficult to observe in edge-on galaxies because of the line-of-sight integration.

WAMSTEKER: Referring to your remark that these extended HI warps and envelopes could represent a phenomenon which only takes place in the gas, I would like to point out my results on NGC 5236. For this galaxy we find ordered optical features corresponding to the warped HI at distances at least out to radii of 40 kpc (r > 2R Holmberg). Some of this seems to be in the form of what is apparently diffuse stellar material. Possible HII regions seem to be indicated in other places. This appears to rule out any process that involves only the gas. The presence of HII regions - still to be confirmed by spectra - would also indicate recent star formation in the outermost regions of the galaxy.

SANCISI: There are well-known cases, as already mentioned, of warped "old" stellar disks, and there may also be, as you point out, some recent star formation in the region of the HI warp. But in isolated systems, like NGC 5907, the bending seems to affect primarily the HI layer.