NEUTRAL HYDROGEN IN EXTERNAL GALAXIES

Lecture notes by J. M. van der Hulst, July 25, 1978.

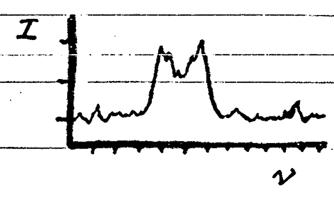
In 1945 van de Hulst predicted the 21-cm transition of neutral atomic hydrogen (HI). A few years later the detection of the HI line was reported by American, Dutch and Australian observers. (see Nature 168, 356-358, 1951). The first detection of extragalactic HI was obtained from the Magellanic Clouds (Kerr and Hindman, 1953).
Since then a bewildering amount of information on the global HI properties (total content of HI) and detailed HI properties (spatial distribution and kinematics of HI) of external galaxies has become available from observations that vary in angular resolution from 0.°5 to 25".
The first thrust to our understanding of the global properties of the HI and related parameters of external galaxies* has been given by observations with the Green Bank 300' telescope (10' beam) and the Nancay telescope (24'x4' beam) of a large number of galaxies. A good review is given by M.S. Roberts in his chapter in SSS IX (Galaxies and the Universe). The results of the French work are basically described by Balkowski (1973).
In the first part of the lecture I will briefly summarize the main results. These notes will cover this only schematically. (section 1)
In the late 60's, early 70's aperture synthesis instruments (Owens Valley, Cambridge, Green Bank, Westerbork) became available and enabled us to actually map the

*) I systematically mean spiral and irregular galaxies.

HI emission in a few dozen relatively nearby galaxies in greater detail. (With single dishes only our closest neighbours, the Magellanic Clouds and the Andromeda nebula, can be observed in detail). The detailed mapping of the HI in galaxies enabled studies of the kinematics, revealed that the HI is distributed in spiral arms (Oort 1974), and started to show that both the distribution and the motions of the HI in galaxies are of a great variety, which hampers a classification of galaxies on the basis of simple physical parameters. A review by van der Kruit and Allen (to appear in Ann. Rev. Astron. Astrophys. 1978) and the thesis of Bosma (1978) give a good overview of what we may have learned from studying the HI in galaxies in detail. I will summarize the basic results in the second part of the lecture (section 2.)

1. Integral properties.

<u>Measured</u> <u>quantity</u>: beam averaged intensity as a function of frequency. (frequency transforms into radial velocity)



CAUTION: radio astronomers use: $c\frac{\Delta\nu}{\nu_0}$

optical astronomers use: $c\frac{\Delta\lambda}{\lambda_0}$

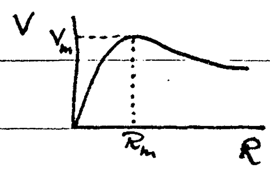
(c: speed of light, ν_0: line rest frequency, λ_0: line rest wavelength)

Assuming the object (galaxy) is unresolved one can determine the systemic velocity (V_s), the HI mass (M_{HI}) and the total mass (M_T).

a. V_s : generally taken as the midpoint velocity of the profile. The errors are, depending on signal to noise, often much less than 10 $km\,s^{-1}$

b. M_H : assuming the HI is optically thin (no self absorption) the profile integral provides M_H via: $M_H = 2.356 \times 10^5 D^2 \int S\,dV$ (D = distance in Mpc, S = flux density in $10^{-26} W m^{-2} Hz^{-1}$ (Jy), V = radial velocity in $km\,s^{-1}$)

c. M_T : basically $M_T = C V_m^2 R_m$ where C is a proportionality constant, V_m a characteristic velocity and R_m a characteristic radius. Given a certain rotation curve V_m and R_m could denote the turnover velocity and radius (e.g. Brandt model).



The value of the proportionality constant is not clearly determined and depends on the mass distribution of a galaxy and the way V_m and R_m are determined.
Different authors use different methods to determine M_T. Application of these methods to one profile give answers that differ by at least a factor 1.5 to 2.
The basic idea is: a. the profile width gives an indication of V_m
b. the optical diameter gives an indication of R_m

3 examples:

$$M_T = 3 \times 10^{-5} \left(\frac{d}{kpc}\right)\left(\frac{\Delta v}{\sin i}\right)^2 \cdot 10^9 M_\odot \quad \text{(Balkowski, 1973)}$$

$$M_T = 1.7 \times 10^{-2} \left(\frac{D}{pc}\right)\left(\frac{d}{arcm}\right)\left(\frac{\Delta v}{2 \sin i}\right)^2 M_\odot \quad \text{(Roberts, SSS IX)}$$

$$M_T = 9.3 \times 10^3 \left(\frac{D}{Mpc}\right)\left(\frac{0.64\,d}{arcm.}\right)\left(\frac{\Delta v_{1/2}}{\sin i}\right)^2 M_\odot \quad \text{(Dean and Davies, 1975)}$$

with d: Holmberg diameter, i: galaxy inclination, Δv: full width of the profile at zero intensity, $\Delta v_{1/2}$: full width at half intensity.

These parameters can be correlated with other integral properties of galaxies as: L (total blue luminosity), t (Hubble type, C_0 (color).

Some "global" correlations are found:

a. M_T correlates with L: most massive galaxies are most luminous.

b. M_H/M_T c.w. t: late type galaxies have a larger fractional HI conten

c. M_H/L c.w. t: later type galaxies have ~~lower~~ higher M_H/L (except Sd, Sdm (Shostak 1978, Astron. Astroph. in press)).

b. and c. may indicate a (s) lower star formation rate in late type galaxies.

Fisher and Tully (1975) observed 241 DDO dwarf galaxies. They concluded that dwarf galaxies are more hydrogen rich than large late type spirals. They also find that M_T/L for dwarfs is approximately constant and not significantly different from "non-dwarf" galaxies.

Both the non-dwarf and dwarf samples show that there is an upperlimit of about $2 \times 10^{10} M_\odot$ to the HI content of a galaxy.

2. HI distribution and kinematics.

a distribution.

Early observations at moderate resolution of M31, M101, and NGC2403 revealed a deficiency of HI gas in the central part (see Roberts sss IX and references therein). Possible explanations are: the hydrogen is mainly in molecular form, a hot galactic wind sweeps the gas from the central regions, very effective starformation depletes the gas in central regions of galaxies. Based on a larger sample Bosma (1978) concludes that earlier type galaxies have a much higher ratio of total mass surface density to hydrogen mass density (σ_M/σ_{HI}). In fact no galaxy with a prominent nuclear bulge has (so far) detectable HI ($\sigma_{HI} \lesssim 1\ M_\odot pc^{-2}$). This facts suggests an analogy with elliptical galaxies which have undetectable or only small amounts of HI. (Knapp et al. 1977 and references therein).

Concerning the disk of a galaxy: HI syntheses of M31, M33, M51, M81 and M101 (Oort 1974, Allen 1975) showed that the HI exhibits a distinct spiral structure, well correlated with the spiral structure in the optical. HI and HII do correlate on a large scale, but on a small scale one finds sometimes HII regions at the edges of dense HI concentrations (M31, M33) and sometimes bright HII complexes at the positions where bright HI concentration occur (M101). This is probably a combination of resolution effects and selective absorption in the optical. The average HI surface density for most galaxies seems in general to drop with increasing distance from the center in the same way as the total mass surface density. In many cases this goes more or less as an exponential disk.

The outer parts of galaxies are very different from galaxy to galaxy. Many galaxies are known now to have a warp in the HI layer; Warps are found either by observing edge-on systems and actually measuring the z distribution of HI (Sancisi 1976) or can be recognized from the kinematics (Rogstad et al. 1974). In the sample of 32 spiral galaxies discussed by Bosma (1978), 13 are warped of which 3 cases are uncertain. Another phenomenon is a large scale asymmetry, or the presence of bridges and t(r)ails. This occurs mainly in galaxies that are members of small groups with galaxy separatio of order 50-100 kpc. Notable examples are M81, M101, N4631.

Concerning the HI dimensions of a galaxy: it is in general true that the HI diameter (measured at a level of 100 K kms^{-1}) is equal or larger than the Holmberg diameter (measured at 26.5 mag. arcsec^{-2}) The average ratio: $d_{HI}/d_{Ho} = 1.5 \pm 0.5$. No correlation exists with type. A better estimate is obtained from correcting the diameters to face on The ratio of HI diameter to photometric diameter (from RCBG II, de Vaucouleu et al. 1976) then is 2.2 ± 1.1.

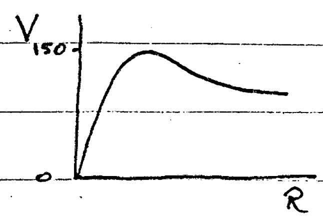
Before discussing the kinematics a note of caution concerning instrumenta effects should be given: a. for many galaxies the scale-length over which σ_{HI} and the HI velocity varies in the inner parts is often of the same order as the beam size; this prohibits a proper measurement of both σ_{HI} and V_{HI} the net effect being that the HI contrast in case of a central deficiency is lowered and that the measured velocity is lower than its actual value (see Bosma 1978, ch. 3).

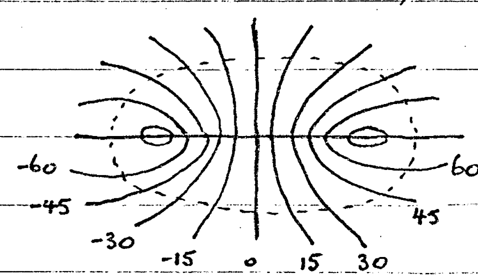
b. the study of the outer parts of the HI in galaxies is often limited by sensitivity, the weakest levels detectable with synthesis instrumen, being of order 5×10^{19} atoms cm^{-2} column density.

c. Presently used reduction techniques to evaluate profile paramete from synthesis data tend to discriminate against broad and weak profiles.

b. kinematics.

The standard picture of a galaxy is a flattened, axialsymmetric system in circular differential rotation. For such a galaxy the rotation curve and velocity field (map of lines of equal radial velocity) would look as follows: (assumed $i \sim 30°$)





However, not many galaxies do show only circular rotation as fig 5.1 of Bosma (1978) clearly illustrates. The type of non circular motions he notes are:

ex: M81, M51 → ⓐ motions associated with spiral arms (density wave streaming

ⓑ large scale symmetric deviations: kinematical major axis changes w radius

NGC4736, NGC4151 → (i) major axis pos. angle changes in inner parts and minor axis not ⊥ major axis: oval distortion in mass distribut.

M83, NGC 5033 → (ii) major axis pos. angle changes in outer parts: kinematical warp (see Rogstad et al. 1974)

M81, NGC4631 → ⓒ large scale asymmetries: mainly in outer parts and usually attributed to tidal interaction

d. small scale asymmetries : irregular in nature and $\lesssim 20\ kms^{-1}$

These asymmetries clearly hamper the determination of reliable rotationcurves-and hence the determination of the distribution of mass surface density. Another problem in the determination of $\sigma_M(R)$ is that no information exists on the 3 dimensional mass distribution.

The way to determine a rotationcurve from a velocity field is described by Warner et al. (1973). The measured radial velocity is $V_{Rad}(R,\theta) = V_s + V_c(R)\cos(\theta-\psi)\sin i$

with R: radius, ψ: maj. axis pos. angle, i: inclination, θ: polar coordina with respect to maj. axis. The procedure is to adjust i, ψ, V_s, and the position of the center of the galaxy such that the values of $V_c(R)$ in a given annulus of radius R and width dR has the lowest dispersion around the mean $\overline{V_c}(R)$.

Given the rotation curve it is possible to evaluate $\sigma_M(R)$ and the cumulative mass within a given radius R: $M(R)$ by fitting a specific mass model. (For mass models see Shu et al. 1971, Nordsieck 1973 and Bosma 1978). One can also evaluate the kinetic energy $E(R)$ and angular momentum $H(R)$.

Bosma in addition defines a parameter $V_m = (2E(R_0)/M(R_0))^{1/2}$ where R_0 is the last measured point on the rotation curve. V_m does not vary much with R between $0.5\,R_0$ and R_0 and is thus a better determined quantity than V_{max}, the turnover velocity.

Results: 1. Almost all rotation curves are flat.

2. V_{max} does not clearly correlate with type, nor does the shape of the rotation curve as Roberts and Rots (1973) suggested. Though Scd galaxies tend to have a lower V_{max} than the earlier types, the spread of V_{max} within a given type can be as much as a factor 2.

3. M(R) increases approximately linearly with R.

4. V_m is independent of type but depends on L. (this is essentially the linewidth - abs. magnitude relation found by Fisher and Tully (1977)

5. M_T/L is independent of type contrary to the conclusion of Brosche and Reinhardt (1977). The however evaluate M_T from integra profiles and hence assume a declining rotation curve. They als use a correlation R_{max}/R_{opt} with type. This correlation is not clearly supported by the rotation curve analyses of Bosma (1978).

6. $M(R)/L(R)$ increases with radius and can reach values as much as 100 in the outer parts of galaxies.

7. σ_H/σ_{HI} correlates with type in the inner parts (central HI depression and with V_m^2 in the outer parts (galaxies with high V_m and low σ_H/σ_{HI} (outer part) have not yet been found)

Some Conclusions: Given the large variety of deviations from circular motions and deviations from axial symmetry a proper determination of precise rotation curves from 21-cm line observations is difficult. The general lack of HI in the centers of galaxies and the large velocity gradient there (often on a scale comparable to the beam, prohibits a proper evaluation of the rotation curve in the inner parts. The hope to establish a dynamical classification parallel to the Hubble sequence has decreased given the lack of correlation between physical parameters and Hubble type. Many, often isolated galaxies have warps. This raises again the question of formation and maintenance of warps.

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