The Gas Content of Galaxies

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When we look at a galaxy on the Palomar Sky Survey, for example, nearly all the light that we see originates in the stellar component. In nearby spirals, we can sometimes see emission from large HII regions. I am going to talk today however about the unseen component, primarily neutral hydrogen with a cursory mention of the molecular component; I will leave out the details of the ionized gas studied via optical emission lines.

To start with, we have to be sure that everyone has some idea of what a galaxy is. For perspective, we can think that the typical galaxy has properties on the order of:

diameter	D	$\sim$ 15-40 kpc.
total mass	M_T	$\sim 2 \times 10^{11}\ M_\odot$.
HI mass	M_H	$\sim 5 \times 10^{9}\ M_\odot$.
luminosity	L	$\sim .5\text{-}1 \times 10^{10}\ L_\odot$.

The spectrum of galaxian integral properties is actually quite large, but let's stick with these average values.

What does a galaxy look like? And what does morphology have to do with evolution, environment or initial conditions? The taxonomy of galaxies is pretty subjective, but it can be helpful in making a first stab at categorizing different types of galaxies. Most galaxy classification systems are based on that of Edwin Hubble, and somehow follow along his "tuning fork" diagram.

There are basically four types of galaxies:

Elliptical galaxies have a spheroidal appearance with little or no evidence for internal structure or extinction (dust). The images have complete rotational symmetry and usually we assume that two of the axes are equal with the third smaller (oblate spheroid). The light distribution is characterized by a smooth gradient of surface brightness from the nucleus outward, of the form

$$I = I_o (r/a + 1)^{-2}$$

where r is the nuclear distance and a is a scale factor. There is no suggestion of resolution into bright blue stars or knots. Subclassification from E0 to E7 is based on the geometry of the projected image.

Lenticular or S0 galaxies also show a smooth image with no evidence of dust. However, the spheroidal or bulge component is now complemented with a flat or disk component. These galaxies differ from ellipticals in their luminosity gradients. Usually three zones of luminosity are evident: first, a nucleus; then an intermediate zone of lower surface brightness (the lens); and lastly, a faint, extensive outer envelope. In many respects, lenticulars represent an intermediate class between ellipticals and spirals (but nobody is saying that a galaxy evolves from E to S0 to Sp or vice versa).

Spiral galaxies are characterized by the presence of spiral arms extending outward from a nucleus and possibly or not, a bar, accounting for the two coarse divisions into barred and unbarred spirals. Each of these two categories is subdivided according to the degree of central concentration and the openness of the spiral arms into types Sa, Sb, and Sc. The spiral arms first emerge in the Sa galaxies where smooth arms are tightly wound, forming nearly circular patterns around an amorphous central region. In Sc galaxies, we see the dominance of highly branched, well differentiated multiple spirals arms that are open and well resolved into stars and HII regions, with lots of visible dust. In Sc's, the nucleus is small and inconspicuous. Sb galaxies are intermediate between Sa's and Sc's (and in fact there can also be further division into intermediate categories Sab's and Sbc's).

Irregular galaxies are classified as such because of their lack of rotational symmetry. There are actually two varieties. The Irr I's show no circular symmetry or prominent spiral structure but they are highly resolved into O and B stars (hot, blue, young) and HII regions. The Irr II's are peculiar, often possess large amounts of obscuring dust, and in many cases may be undergoing some dramatic event like an explosion or tidal interaction.

Astronomers also like to further confuse the issue by referring to ellipticals and lenticulars as "early type galaxies" and to differentiate among spirals similarly, with Sa's being "early" spirals and Sc's being "late". Undoubtedly, we see the remnant of old ideas about galaxy evolution along the Hubble sequence. Today this only serves to distinguish the shop-talkers from the novices.

The source for most of my slides of the different morphological classes of galaxies is The Hubble Atlas of Galaxies (Sandage, 1961, Carnegie Inst. of Washington).

Since the lenticulars are in some senses more spiral-like than elliptical-like, or at least are transitionary, we can lump them with the spirals and crudely compare ellipticals and spirals:

Ellipticals	Spirals
elliptical shape	disk and spiral arms
smooth luminosity gradient	disk and bulge components
light dominated by red stars	light dominated by blue stars
no recent star formation	evidence of recent star formation (HII regions, etc.)
little or no gas	gas and dust
found in cluster cores	avoid central regions of clusters

From the above table, it is apparent that elliptical galaxies have little or no HI gas. In fact, most experiments done on ellipticals have been detection surveys with a lot more negative results than positive ones. We'll come back to ellipticals in a little bit. But first let's take a look at the distribution of gas in spirals Sa to Sc.

In studying the HI content of galaxies, we observe photons emitted at a rest frequency of 1420.4058 MHz redshifted to some lower frequency corresponding to the Doppler shift of the galaxy as it recedes from us in the expanding universe. The 21 cm line of neutral atomic hydrogen is produced by radiative transitions between the two hyperfine levels of the ground electronic level. In the upper hyperfine level, the electron and proton spins are parallel; in the lower, they are antiparallel. A photon is emitted when the electron flips its spin to be antiparallel. The spontaneous transition probability is $2.869 \times 10^{-15}\ s^{-1}$! But there is so much HI out there that in fact for spiral galaxies between here and the Hercules cluster (z=.03 or about 200 Mpc), observing the redshifted 21 cm line is the fastest way to get a galaxy redshift.

The integrated HI profile which we observe when a galaxy is smaller than the telescope beam is affected by two things: first, the HI distribution within the galaxy $\sigma_H(r)$ and secondly, the rotation curve V(r). The general concept of a rotation curves divides a galaxy into three zones: first, a central region of solid body rotation; second, a turnover point where the rotation curve flattens out; and third, an outer region where the rotation curve may be still rising, may be flat, or may fall off (Keplerian). The nature of rotation curves is still a hot topic because of the consequences on calculations of the total mass within a galaxy, since the rotational velocity of stars and gas at any radius is reflective of the mass interior to that radius. If the outer regions of the galaxy can look at the mass interior as concentrated toward the center of the galaxy, then we expect the rotation curve to fall off towards the outside in a return to Keplerian motion and the galaxy's mass is relatively small. However, if the distribution of non-luminous (dark) material is sufficiently widespread, or there is a galaxian halo, then the rotation curve will remain flat or even continue rising as far out as we can trace it, and the mass of an individual galaxy is much larger than that accounted for by its visible light (see: Rubin, June 1983, Scientific American, 248, 96).

Examples of rotation curves show that most of them are flat. The kinematics is dominated by differential rotation over the whole disk, but deviations from circular motions are also evident in the central regions, in arms, and in bars (eg. Bosma, 1981, Astron. J. 86, 1791).

Along with the rotation curve goes the actually distribution of HI as a function of radial distance from the center. The HI in most cases does not peak toward the center, but rather shows a central depression. A nice illustration of such ring structure is the radiograph of the HI in Andromeda, M31, by Unwin (1980, MNRAS 192, 243). The advent of the WSRT and the VLA have now made it possible to map out the HI distrbutions in a number of nearby galaxies (eg. Bosma, ibid.). The distribution of HI in ordinary spirals is normally characterized by this deficiency in the central regions and by structures associated with the spiral arms in the main part of the disk. The central depression in our own Galaxy occurs within a radius of 3 to 5 kpc, and seems to be more pronouced in high luminosity early-type systems which possess large bulges. The origin of the central hole is still a matter of debate. The "missing" HI gas may actually be molecular. We known in our own galaxy that a substantial amount of molecular gas resides in the central 1 kpc. The few observations of CO in other galaxies which are yet available imply a concentration of H_2 precisely in the regions where the HI falls off (eg. Young and Scoville, 1982, Ap. J. 258, 467).

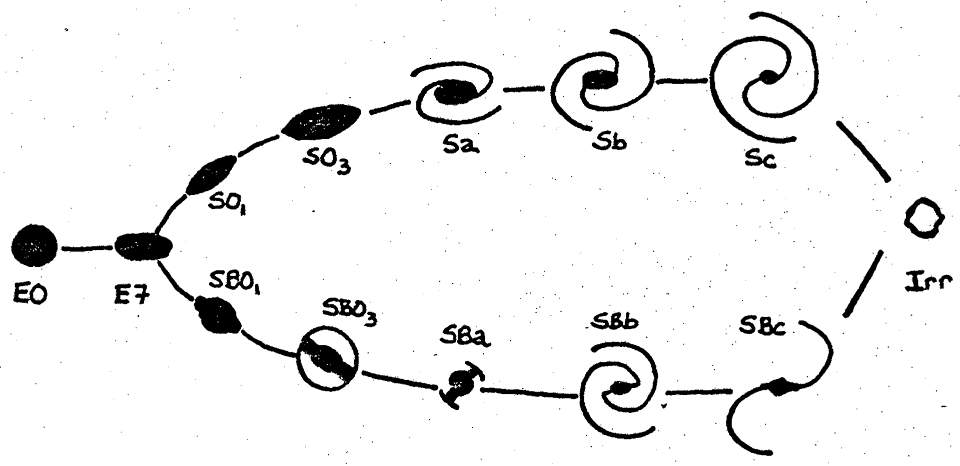
As seen also in our own galaxy, the HI extends out farther than the other population I objects, HII regions, young stars and radio continuum emission. Large-scale deviations from axial symmetry, probably evidence of oval distortions or warping of the disk are often apparent. Most of the edge-on galaxies studied to date show evidence for warps (NGC 4244, 4565, 4631, 5907). Further asymmetries or even lop-sidedness may be coincident in the HI, continuum and optical light distributions. A number (but not all) of HI appendages have been explained in terms of tidal interactions among galaxies in loose groups. In the Local Group, the HI bridge between the Magellanic Clouds and the Magellanic Stream (Mathewson, Cleary and Murray, 1974, Ap. J. 190, 291) are probably the result of tidal forces. Such encounters are efficient mechanisms for the removal of a substantial fraction (50%) of a galaxy's interstellar medium when the orbital motion is direct with respect to the rotational, the perigalactic distance is small ($\sim$20 kpc) and the relative velocities of the galaxies is low (200 kms^{-1}). Good examples of HI streams which have been successfully modelled in terms of tidal interactions in other systems are NGC 4631/56 (Weliachew, Sancisi and Guelin, 1978, Astron. Ap. 65, 37), NGC 4038/9 (van der Hulst, 1979, Astron. Ap. 71, 131) and the Leo Triplet (Rots, 1978, Astron. J. 83, 219; Haynes, Giovanelli and Roberts, 1979, Ap. J. 229, 83). Tidal encounters can remove gas from a galaxy which previously had a lot of gas; a galaxy which had little or no gas can also inherit some from its neighbor. So certainly in groups where the relative velocity is low but the space density is high, the HI content of a galaxy can be influenced by its environment.

As we go to early type galaxies (Sa, S0, E), the HI content (M_H/M_T) decreases and the emission becomes increasingly difficult to detect. In lenticular galaxies, the HI is often found in a ring whose radius is roughly equal to the extent of the optical image. Most ellipticals have no detectable HI. The few that do often have some peculiarity about their optical appearance making their classification suspect. The elliptical NGC 4278 (Raimond, Faber, Gallagher and Knapp, 1981, Ap. J. 246, 708) shows an HI disk with some large-scale structure, possibly suggesting spiral arms, and a depression in the central, optically-bright region. The velocity field resembles that seen in spirals.

Another aspect of the study of the HI distribution within spiral galaxies is the comparison of the relative HI content of galaxies in different environments. We have tried to compare the HI content of galaxies in rich clusters with that of a sample of so-called isolated galaxies. By observing the HI emission from galaxies in both samples, we define a deficiency parameter as the deviation in the HI mass of a given cluster galaxy with respect to that expected for a comparison isolated galaxy of similar optical characteristics, usually optical luminosity and surface brightness or linear diameter.

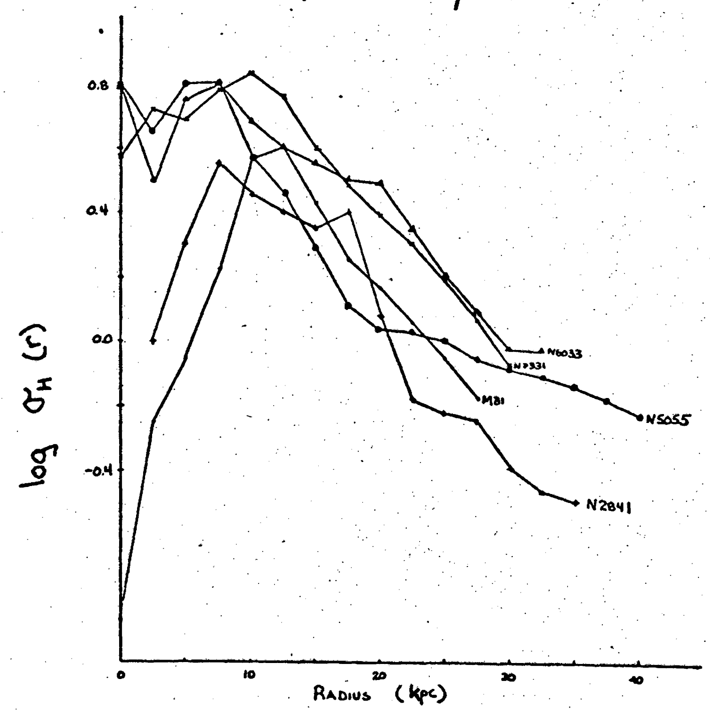
The results of such a comparison for a number of clusters show that, in some clusters the galaxies are highly HI deficient, while in others, the galaxies are normal with respect to the isolated ones. We have tried to figure out what is going on. There are three mechanisms which might cause removal of the gas within a galaxy: 1) tidal interactions; 2) galaxy-galaxy collisions; 3) galaxy-intergalactic medium interactions. Tidal interactions are certainly important in groups of galaxies, but in clusters the velocity dispersions are too high. The Hercules supercluster provides a great testing ground for the latter two mechanisms. At the same distance are two rich clusters, A2151 with a high space density, nice for galaxy-galaxy collisions, but no x-ray source, and A2147 with a lower space density but an extended x-ray source implying the presence of a hot (10^8 K) intergalactic medium. Selection effects should be minimized because the galaxies are all at the same distance and hence are roughly of the same apparent magnitude and angular diameter. In fact, we see strong deficiency in A2147 whereas most of the galaxies in A2151 have a normal HI content (Giovanelli, Chincarini and Haynes, 1981, Ap. J. 247, 383).

The galaxy-intergalactic medium interactions come basically in two varieties also: the ram pressure sweeping of the interstellar gas as the galaxy moves through the relatively stationary hot intergalactic gas; and evaporation, simply conduction across the corona to the disk. Both predict the decrease of HI size which is evident in galaxies in the Virgo cluster (Giovanardi, Helou, Salpeter and Krumm 1983, Ap. J. 267, 35; Giovanelli and Haynes 1983, A.J. in press). A preliminary result in support of the ram pressure sweeping hypothesis for Virgo is the correlation of HI deficiency with the velocity of the galaxy with respect to the cluster. The ram-pressure is proportional to the product $\rho_{igm} V_{\perp}^2$, where ρ_{igm} is the density of the intergalactic medium and $V_{\perp}$ is the component of the galaxy's velocity with respect to the intergalactic medium which is perpendicular to the disk. Hence, with the obvious projection effect problems, deficiency and relative velocity should be correlated in a ram-pressure sweeping model, whereas evaporation makes no such prediction.



Hubble System of Galaxy Classification

HI surface density distribution



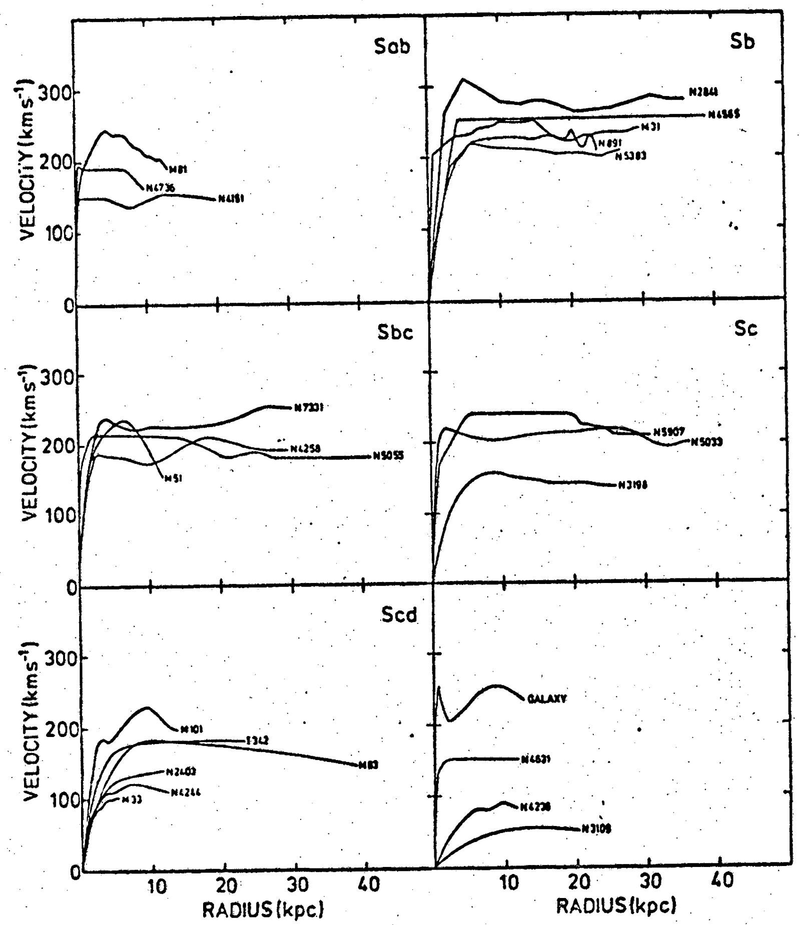


FIG. 3. Rotation curves of 25 galaxies of various Hubble types.

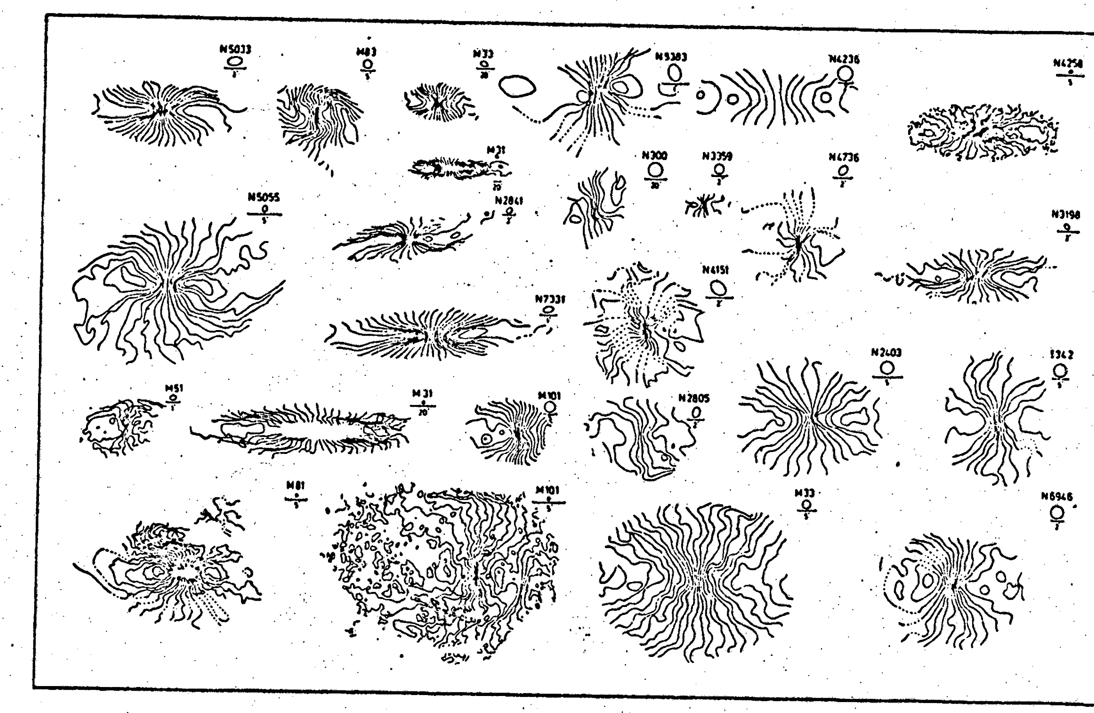


FIG. 1. Velocity fields of 22 spirals taken from the sources listed in Table I. All pictures have been oriented such that the major axis is roughly horizontal. The hatched areas represent the beamwidths.

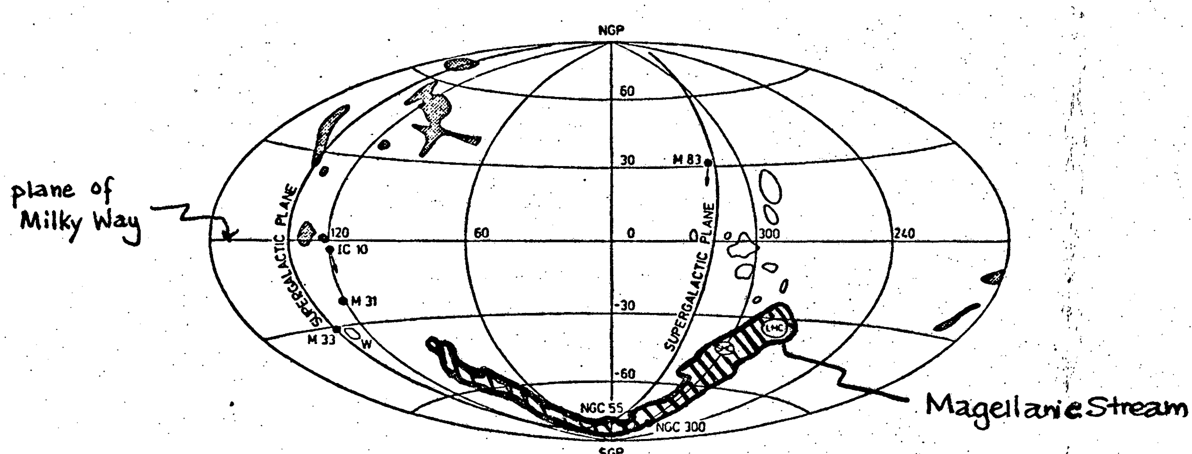


Fig. 3.—On this Aitoff projection in galactic coordinates are drawn: (1) the high-velocity H I clouds (cf. Hulsbosch 1972) (*crosshatched areas*); (2) the plane of the Local Supergalaxy (*thick line*); (3) the direction of the H I tails on NGC 300, M83, and IC 10 (*arrows*); (4) the Magellanic Stream (*outlined areas*); (5) the H I cloud discovered by Wright (1974) near M33, labeled W.

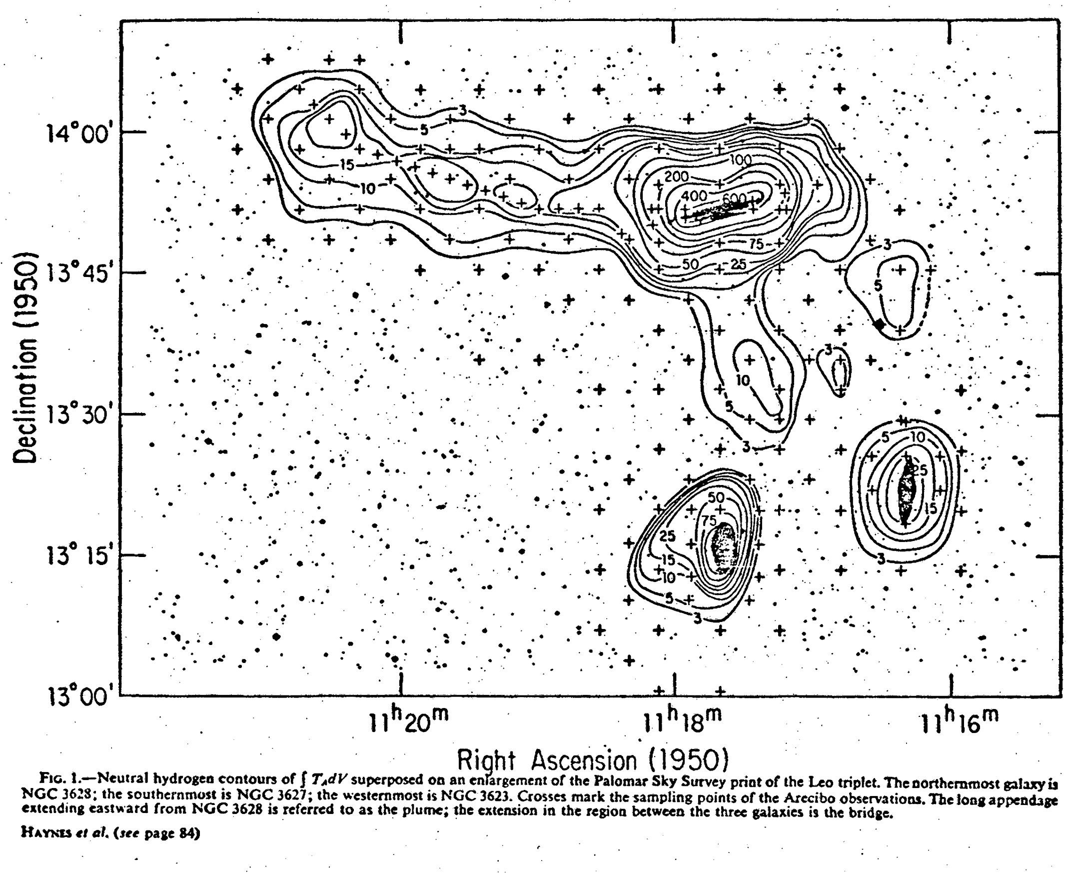


Fig. 1.—Neutral hydrogen contours of $\int T_A dV$ superposed on an enlargement of the Palomar Sky Survey print of the Leo triplet. The northernmost galaxy is NGC 3628; the southernmost is NGC 3627; the westernmost is NGC 3623. Crosses mark the sampling points of the Arecibo observations. The long appendage extending eastward from NGC 3628 is referred to as the plume; the extension in the region between the three galaxies is the bridge.

Haynes *et al.* (*see* page 84)

PLATE 1

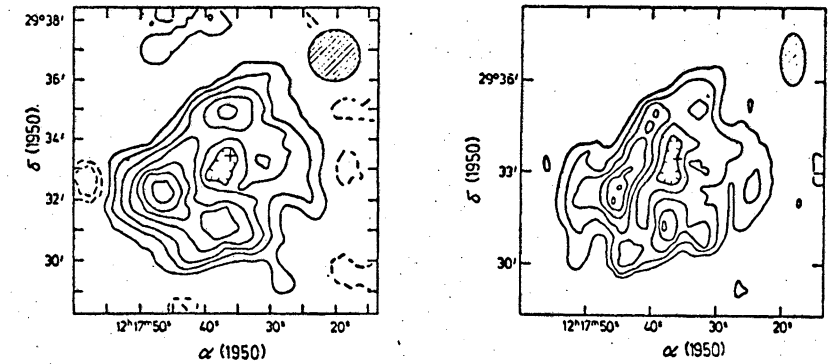
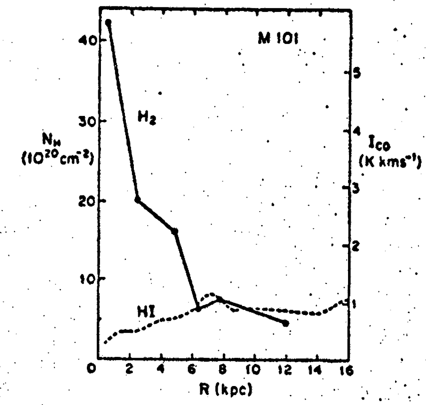


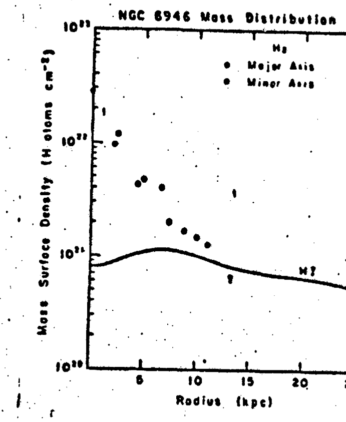
FIG. 2a FIG. 2b

FIG. 2.—(a) The distribution of the total column density of neutral hydrogen in NGC 4278 obtained by integrating the smoothed maps. The beam size is indicated in the upper right-hand corner. The contour interval is 2.37×10^{19} cm^{-2}. Negative contours are dashed; the zero contour is not given. The cross indicates the position of the nuclear source. (b) Neutral hydrogen distribution in NGC 4278 obtained by integrating the full-resolution maps over those areas where $T_b > 0.15$ K in the smoothed maps. The contour interval is 3.79×10^{19} cm^{-2}.

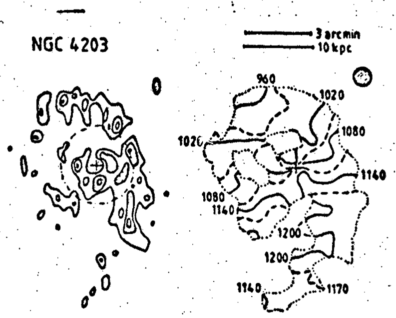
From Raimond et al. 1981 Ap J 246, 708

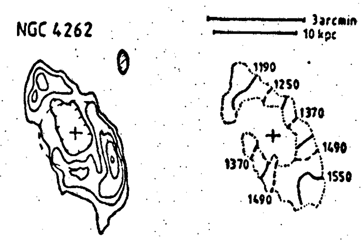
N4278 is type E1





4. COMPARISON OF H_2 AND HI SURFACE DENSITIES IN M101 (SOLOMON ET AL. 1982)





N4203 type SO_2

N4262 type $SBO_{2/3}$

dashed circle is optical extent

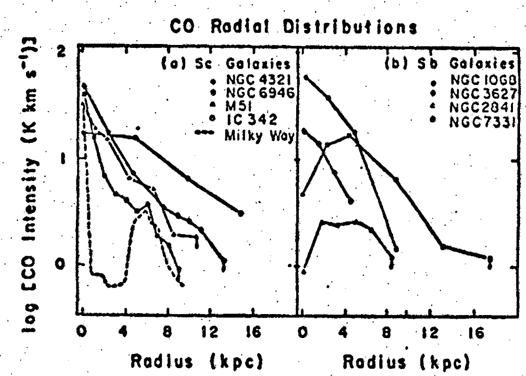


Figure 3. (a) Observed CO radial distributions in 4 relatively face-on Sc galaxies do not show a molecular "hole" like that in the Milky Way at R ~ 1 to 4 kpc. (b) Central CO holes are observed in several Sb galaxies with large nuclear bulges.

HERCULES SUPERCLUSTER

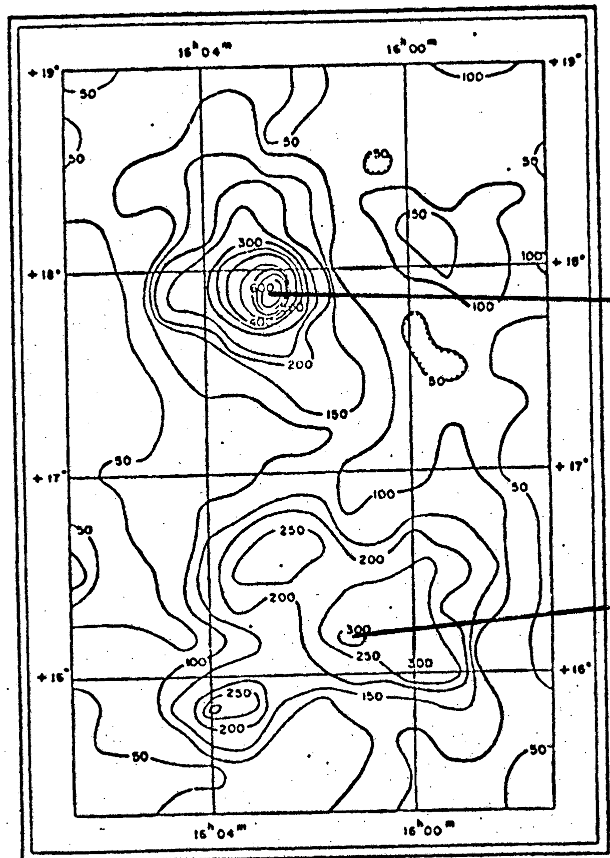


FIG. 9.—The Hercules cloud of galaxies. Number of galaxies per square degree.

A2151
higher space density
no cluster X-ray source

A 2147
lower space density :
. cluster X-ray source

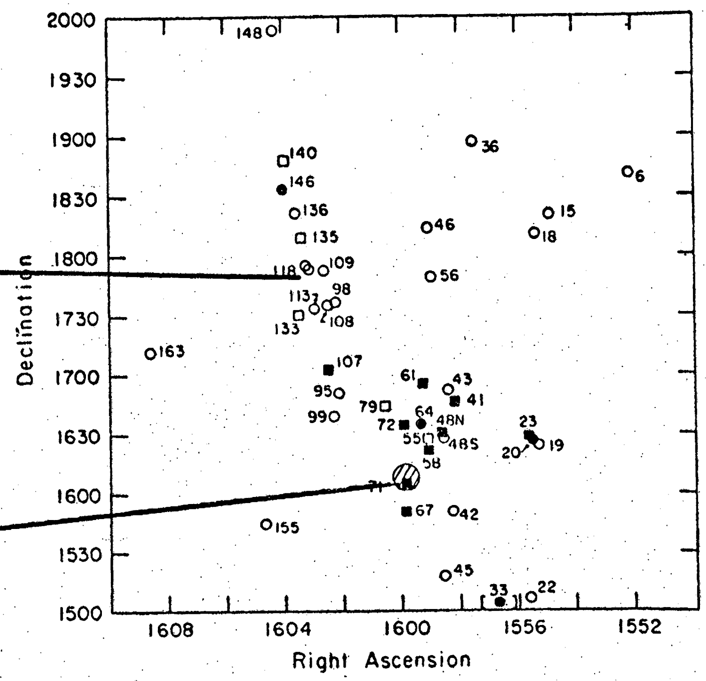
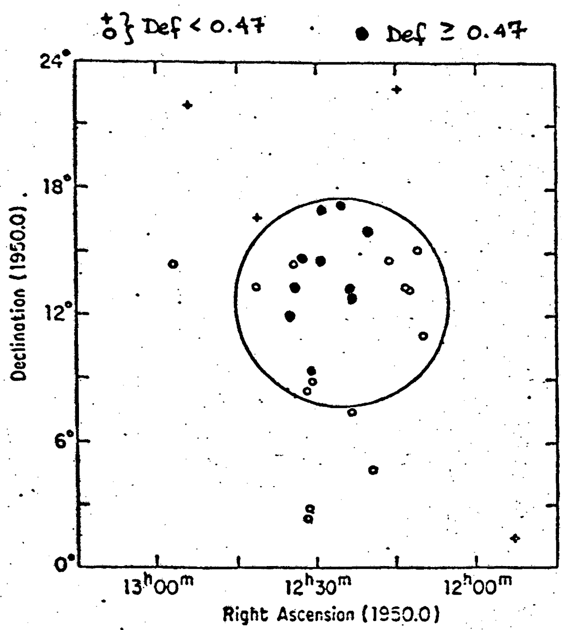


FIG. 5.—The Hercules supercluster region in the CGCG field 108. *Unfilled circles*, detected galaxies with *Def* <0.48 (i.e., deficient by less than a factor of 3); *filled circles*, detected or tentatively detected galaxies with *Def* >0.48; *unfilled squares*, undetected galaxies with lower limit of *Def* <0.48 (galaxies observed for relatively insufficient integration times are in this group); *filled squares*, undetected galaxies with lower limits of *Def* >0.48. The X-ray source in A2147 is represented by a circle with radius roughly representative of the isothermal core radius as reported by Jones *et al.* (1979). The numbers by each symbol identify the galaxies by their CGCG order in the field 108.

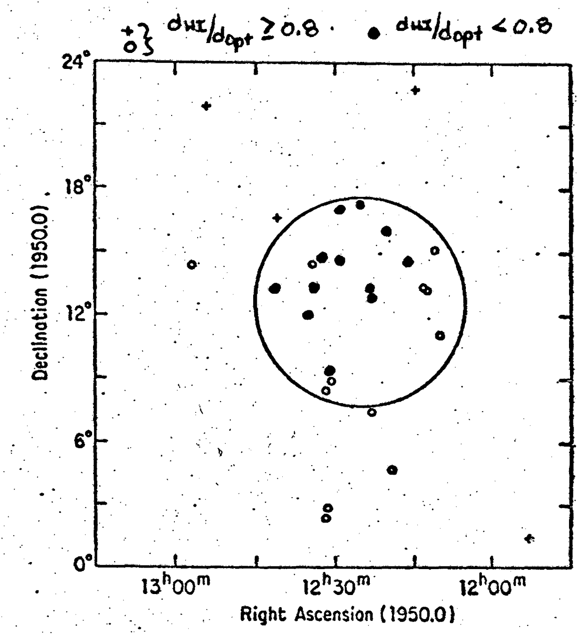
$$DEF = \log\langle M_H/L\rangle_{T,SB} - \log(M_H/L)_{OBS}$$

↑ from isolated galaxy sample

Deficiency



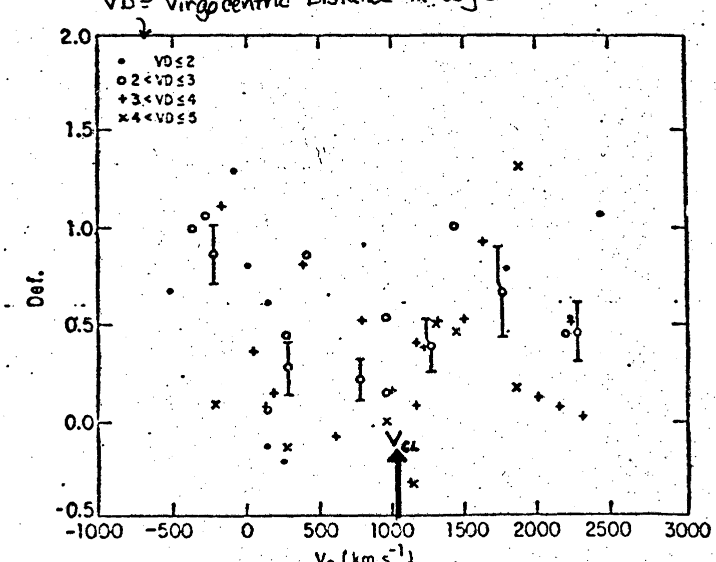
HI to optical size



Circle is 5° radius centered on Virgo cluster

Here $\text{Def} = \log M_H^* - \log M_H(\text{obs})$ where M_H^* is the HI mass of a comparison galaxy of the same linear HI diameter.

VD = Virgocentric Distance in degrees



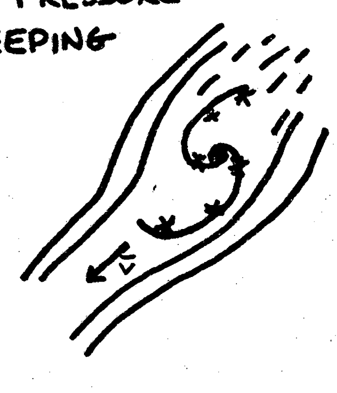
Observed radial velocity

cluster velocity is:

$V_{cl} = +1026 \text{ kms}^{-1}$

Averages of 500 kms^{-1} bins are shown with error bars (error on the mean).

RAM PRESSURE SWEEPING



$V_\perp$ = component of $\bar{v}$ along axis of galaxian disk

ρ_{igm} = density of intergalactic gas

σ^* = surface density of all mass in galaxy

σ_H = surface density of gas

<u>Sweeping</u> if $\rho_{igm} V_\perp^2 \gtrsim 2 G \sigma^*(r) \sigma_H(r)$.