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# The H I content of lenticular and early-type galaxies: a comparison between field and Virgo cluster samples

**P. Chamaraux**[1], **C. Balkowski**[2], **and P. Fontanelli**[2]

[1] Observatoire de Paris, Section de Meudon, UA 324 – DERADN, F-92195 Meudon Principal Cedex, France
[2] Observatoire de Paris, Section de Meudon, UA 173, Laboratoire d'Astrophysique associé à l' Université Paris VII, DAF, F-92195 Meudon Principal Cedex, France

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**Summary.** The distribution of the global H I contents of a sample of 122 S0 galaxies (31 detections) observed at Arecibo has been studied by means of a new statistical method taking into account the upper limits of detection. The H I contents are defined by the mean H I surface density $\sigma_H$; the method gives the proportion of galaxies having $\sigma_H$ larger than the lowest detectable $\sigma_H$ (here $0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$) as well as the true distribution of $\sigma_H$ above this value.

The first striking result concerns the complete dissimilarity of the $\sigma_H$ distributions and of the average H I contents for the Virgo cluster S0's and for the non-cluster ones. For the latter, we find an average H I content about five times lower than for the non-cluster early spirals; furthermore, the H I content increases significantly by more than a factor of 3 along the de Vaucouleurs numerical sequence of S0 subtypes $-3$, $-2$, $-1$. But for the Virgo S0's, much lower H I contents are indicated by our method, although it is not possible to determine their average value, due to insufficient limits of detection.

If stripping by the intergalactic gas is the cause of the H I deficiency in Virgo, then Sa and S0 galaxies are expected to have analogous deficiencies because of their similar H I spatial distributions; so using a similar statistical method, we have compared the H I contents of 23 S0/a, Sa and Sab galaxies members of the Virgo cluster observed at Arecibo to the H I contents of 70 non-cluster objects having the same respective morphological types. As a result the Virgo early-spirals are found to be H I deficient by a factor 11, compared to only 2.5 for later spirals, and thus they do not contain more H I than the non-cluster S0's. On the other hand, the deficiency of the Virgo cluster spirals is found to decrease continuously from S0/a to Sc, which favours the stripping as its cause and foresees still higher deficiencies for the Virgo S0's than for early spirals.

An analysis of the global H I properties of the non-cluster S0's tends to show that these galaxies extend without discontinuity the sequence of the spirals beyond S0/a, which is in favour of non-cluster S0's having been formed as S0's rather than coming from ancient spirals stripped of their gas. On the contrary, the similarity of the H I contents of the Virgo cluster early spirals and of the non-cluster S0's makes likely that at least a part of the Virgo S0's originated from stripped early spirals. If most of the present Virgo spirals have come from the Virgo Southern extension in the last $4\,10^9$ years, as proposed by Tully and Shaya (1984), then the much smaller percentage of late spirals found in the Virgo extension compared to the Virgo cluster implies that a part of them has been converted into earlier morphological types. Consequently we suggest that a spiral in the Virgo cluster undergoes a shift of $-2$ in its type each $1$–$2\,10^9$ years by stripping by the intracluster medium, a conclusion which is compatible with the data. Thus most of the Virgo cluster S0's could come from early spirals entered into the cluster between 4 and $2\,10^9$ years ago.

**Key words:** H I content – lenticular galaxies – early spiral galaxies – Virgo cluster – H I deficiency

## 1. Introduction

The main difficulty encountered in the study of the statistical H I properties of S0 galaxies derives from the high percentage (~70%) of undetected objects. Up to now, the statistical H I studies on S0's (van Woerden, 1977; Giovanardi et al., 1983) have not fully used the information provided by the upper limits of detection, leading to necessarily limited conclusions. In particular the distribution of the H I contents of the S0's is presently unknown, a quantity needed to understand the nature of these objects. However a statistical method does exist to take properly into account the upper limits of detection (Avni et al., 1980), and, as a matter of fact, a similar method has already been used by Sanders (1980) to derive the distribution of the H I contents of the elliptical galaxies.

In the present paper we apply another very simple method to take into account the upper limits of detection (Chamaraux, 1986), and use it to study and discuss the distribution of the H I contents of 122 lenticular galaxies, observed mainly in the surveys carried out at Arecibo by Giovanardi et al. (1983) and by Chamaraux et al. (1986). The principle of this statistical method is recalled in Sect. 2; the sample of S0's to which the method is applied is presented and discussed in Sect. 3. The results are given in Sect. 4: they show in particular the Virgo cluster S0's to be H I-deficient when compared to the non-cluster ones, and the H I contents of the latter to be about 5 times lower than the ones of the S0/a spirals and to increase along the de Vaucouleurs sequence of types $-3$ to $-1$. In Sect. 5, it is shown that the early spirals in Virgo are H I-deficient by a factor higher than 10, i.e. have no more gas than non-cluster S0's; because of similar spatial

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*Send offprints requests to:* P. Chamaraux distribution of H I, Virgo S0's are expected to present such high deficiencies. From our results, a tentative discussion about the origin of the S0's is presented in Sect. 6. We argue in favor of a primordial origin for the non-cluster S0's; in turn, we consider as likely that a substantial proportion of Virgo S0's comes from stripped early spirals. A general conclusion is given in Sect. 7.

## 2. The statistical method

Our purpose is to determine the true distribution of the H I contents of the S0's. First we have to characterize the H I content by some parameter; we choose the mean H I surface density $\sigma_{\mathrm{H}}$ defined by:

$$\sigma_{\mathrm{H}} = M_{\mathrm{H}} \Big/ \frac{\pi}{4} A_o^2$$

where $M_{\mathrm{H}}$ is the H I mass of the galaxy and $A_o$ its linear optical diameter. The reasons for such a choice will be given in Sect. 4.

In order to obtain the true distribution of the $\sigma_{\mathrm{H}}$'s of the S0's, we then need some statistical method taking into account the limits of detection. Avni et al. (1980) have developed such a method, but since the computation of the uncertainties is rather complex in this method, we have preferred to use another one, in fact quite equivalent to Avni et al.'s one. This method is briefly exposed in Balkowski et al. (1985) and detailed by Chamaraux (1986), with some examples of application. Here we just recall its principle.

Thus we suppose that we look for the distribution of a parameter $x$ for a determined class of objects. In that purpose, a sample of these objects is chosen and observed, and we consider the eventuality in which some objects of the sample are undetected. Then, as a result of the observations, we have at our disposal, on the one hand detected objects, the parameters $x$ of which are known, and on the other hand undetected objects, for each of which only a known limit $x_l$ of its $x$-value has been obtained, such that $x < x_l$ (it is always possible to assume that the $x_l$'s are upper limits). Thus, in the case of non-detections, $x_l$ is the smallest value of $x$ which could be detected in the observation; for each of the detections, one can also define a $x_l$-value in the same way, a value which is also known, but which satisfies to the inequality: $x_l \leq x$. Thus the detection condition of any object of the sample having $x_0$ (known or not) as a value of its parameter and $x_{l_o}$ as a value of $x_l$ is obviously: $x_{l_o} \leq x_o$. Now let us consider all the $\Delta N_t$ objects of the sample having a $x$ parameter equal to $x_o \leftarrow \Delta x/2$, and let us assume that the relative distribution $\Psi_{xo}$ of their $x_1$'s is the same of any $x_o$ value, an assumption which is generally valid in practical cases. Then $\Psi_{x_o}$ is equal to the known relative distribution $\Psi$ of the $x_l$'s for the whole sample. The detection condition allows immediately to compute $\Delta N_t$ from $\Psi$ and from the known number $\Delta N_d$ of detected objects in the interval $x_o \pm \Delta x/2$ (see Fig. 1) by:

$$\Delta N_t = \Delta N_d \int_{-\infty}^{+\infty} \Psi(x_l)\, dx_l \Big/ \int_{-\infty}^{x_o} \Psi(x_l) dx_l$$

where $\Psi$ is treated as a function of a continuous variable, in order to simplify the writing.

The uncertainty on $\Delta N_t$ introduced by the method is characterized by a r.m.s. dispersion: $\sigma(\Delta N_t) = \sqrt{\Delta N_d(1-p)}/p$, with $p = \Delta N_d/\Delta N_t$ (Chamaraux, 1986), a very simple expression which justifies our choice of the present method.

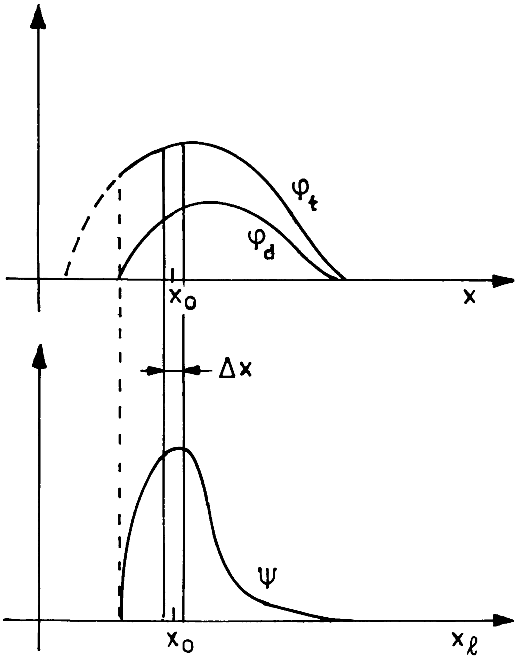

**Fig. 1.** Illustration of the statistical method developed to derive the true distribution $\varphi_t$ of a measured parameter $x$ from its distribution $\varphi_d$ for the detected objects and from the distribution $\Psi$ of its upper limits of detection $x_l$. See text for explanations

## 3. The data

### *3.1. Description of the sample*

The detection rate of the S0's in the H I observations is low; it is therefore of primary interest to know the distribution of their H I contents for values as low as possible, which requires not only detections of low H I contents but also a significant percentage of very low limits of detection, hence H I observations at high sensitivity. The H I surveys of early-type galaxies carried out by Giovanardi et al. (1983) and by Chamaraux et al. (1986) at Arecibo provide a large sample of S0's observed in these conditions. In fact, using our method, there is no advantage in adding to a sample measured at high sensitivity other objects measured with a clearly lower sensitivity. For that reason, and since the sensitivity of the H I observations at Arecibo is about 6 times better than anywhere else, we have defined our final sample adding to the S0's observed in the two surveys few other ones measured at Arecibo by Bieging and Biermann (1977), Biermann et al. (1979), Krumm and Salpeter (1979a,b), Knapp et al. (1979) and Haynes (1981). The galaxy NGC 3900, although not observed at Arecibo, has been added to the sample since it is in the Arecibo declination range and it has been detected elsewhere. Confused or possibly confused S0's have not been considered.

The final sample contains 122 galaxies classified as lenticular in the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs et al., 1976, hereafter RC2), i.e. having numerical types $T = -1$, $-2$ or $-3$ in that catalogue. Among them 62 are located out of any cluster, and 43 are members of the Virgo cluster. On the other hand, the sample contains all the S0's from RC2 but 14, having a fully corrected RC2 diameter $a_o$ greater than 2′ and located within the declination range $-1° \leq \delta \leq 38°$

accessible to Arecibo. The cumulative histogram giving the number of galaxies $N(\geq a_o)$ having a diameter larger than $a_o$ as a function of $a_o$ shows that $N(\geq a_o)$ varies as $a_o^{-3}$ as long as $a_o > 2'$, indicating that the sample is fairly complete to that limit of diameter within the declination range considered.

We measure the H I content by the mean H I surface density $\sigma_H$ expressed in $10^{-3}\,\mathrm{g\,cm^{-2}}$ by: $\sigma_H = 0.739 F_H/a_o^2$. In this formula, $a_o$ is the RC2 apparent major axis of the galaxy expressed in minutes of arc, defined by the brightness level 25 m/□" and corrected to face-on view and for galactic extinction; $F_H$ is the total H I flux in $\mathrm{Jy\,km\,s^{-1}}$.

### 3.2. *The beam corrections*

The majority of the galaxies of our sample have been observed at Arecibo at their central positions only, and their apparent diameters are not small compared to the 3'.2 beam of the instrument. Thus if $F_{H_c}$ is the flux received from a galaxy when pointing the Arecibo telescope at its center, one has $F_H = f_c F_{H_c}$, where $f_c > 1$ is the correction for beam filling. On the other hand, let $F_{H_{lc}}$ be the lowest detectable flux in that central observation of the galaxy; the detection condition is $F_{H_{lc}} \leq F_{H_c}$. Let us define: $F_{H_l} = f_c F_{H_{lc}}$; then the condition of detection is: $F_{H_l} \leq F_H$. If we define $\sigma_{H_l}$ from $F_{H_l}$ in the same way as $\sigma_H$ from $F_H$, the detection condition can be written: $\sigma_{H_l} \leq \sigma_H$. Therefore, the use of our statistical method to determine the $\sigma_H$ distribution of the S0's requires to know the distribution of $\sigma_{H_l}$, and that of $\sigma_H$ for the detected galaxies as well. Then the definitions of $\sigma_{H_l}$ and of $\sigma_H$ show that it is necessary for that purpose to know $f_c$ for each galaxy of our sample. In the case of a galaxy of our sample mapped, or also measured with a radiotelescope having a large beam compared to its dimensions, the derivation of $f_c$ is straightforward since one knows $F_H$ and $F_{H_c}$: 13 galaxies fall in this category. For each of the other 109 galaxies, we have tried to determine a kind of most probable beam correction $f_c$, checking its value from the 13 galaxies with known total $F_H$. Since very little is known about the distribution of the H I gas in the S0's, we have used a very simple model consisting of a gaussian large-scale H I distribution, characterized by an H I diameter $a_H$ within which half of the total H I mass lies; the study of the H I diameters by Fouqué (1983) shows the ratio $a_H/a_o$ depends on the morphological type of the galaxy; for 7 S0's, he obtains: $\langle a_H/a_o \rangle = 1.6 \pm 0.3$.

Assuming the Arecibo beam also gaussian with a HPBW 3'.2 at 21 cm, we have: $f_c = [1 + (0.5a_0)^2]^{1/2}[1 + (0.5b_0)^2]^{1/2}$, where $b_0$ is the RC2 minor axis at the 25 m/□" level in minutes of arc, hence the corrected fluxes $F_{H_{cor}}$. For the 7 galaxies mapped, we can derive directly the total fluxes $F_{H_{tot}}$. For the 6 galaxies observed elsewhere, a beam correction has been carried out in the same way as above, but in this case it is only of a few percent because the beams are large compared to the dimensions of the galaxies; hence their total fluxes with an excellent approximation. Then we obtain for the 13 objects:

$$\overline{\log \frac{F_{H_{tot}}}{F_{H_{cor}}}} = 0.05 \pm 0.07$$

or $0.00 \pm 0.06$ when excluding the discrepant point corresponding to NGC 7743 (the profiles of this galaxy obtained elsewhere than at Arecibo are in fact very uncertain). Thus the agreement is good, despite the large values of $f_c$ ($\bar{f}_c = 2.7 \pm 0.8$). So we can confidently use this correction factor $f_c$ for beam smearing for all our sample galaxies. Of course, our $f_c$ values can be very erroneous in some individual cases, particularly for objects of large apparent dimensions. But the important point for us is that our $f_c$ values are correct on an average, especially if one notes that the mapped galaxies have apparent dimensions significantly larger than the other ones. Obviously, the uncertainties affecting our $f_c$ values introduce some dispersion on $\sigma_H$, that we estimate to 60%; but such a dispersion remains small compared to the observed dispersion on $\sigma_H$ of S0's, whose value is about a factor 4, as it will be shown below.

Finally, the value of the lowest H I detectable flux $F_{H_{lc}}$ of a galaxy observed at Arecibo when pointing at its center (a quantity which is necessary to know the distribution of $\sigma_{H_l}$), has been determined as follows:

(i) For the undetected galaxies, we have adopted: $F_{H_{lc}} = 0.9\sigma$, where $\sigma$ is the r.m.s. noise in the observation (in mJy) as given by the authors and $F_{H_{lc}}$ is in $\mathrm{Jy\,km\,s^{-1}}$. This limit corresponds to a $3\sigma$ maximum height of the profile over a $300\,\mathrm{km\,s^{-1}}$ width. When observed by several authors, we have adopted for the galaxy the lowest $F_{H_{lc}}$ value.

(ii) For the detected galaxies, $\sigma$ is generally not available. So we have adopted the average $\bar{\sigma}$ of the $\sigma$'s for the undetected galaxies of the series of observations given in the corresponding paper. For some galaxies, it happens that $F_{H_c} < 0.9\bar{\sigma}$; in this case, we have taken $F_{H_{lc}} = F_{H_c}$. For those galaxies observed by several authors, the lowest corresponding $F_{H_{lc}}$ has been retained. All the basic observational data, as well as the $\sigma_H$ and $\sigma_{H_l}$ values are entered into Table 1.

## 4. The true distribution of the H I contents of the S0's

### 4.1. *Choice of the H I parameter and applicability of our method*

Before using our statistical method to derive the true $\sigma_H$-distribution of the S0's, two questions need to be answered:

#### 4.1.1. Is $\sigma_H$ the most suitable parameter to characterize the H I contents of the S0's?

First, note that for the spirals, the diameter $A_o$ and the H I mass $M_H$ follow the relation: $M_H = \alpha(T)A_0^2$, $\alpha(T)$ depending only on the morphological type (Chamaraux et al., 1980; Haynes and Giovanelli, 1984). Thus $\sigma_H$ characterizes very well the H I content of a spiral having a given type.

Is there the same correlation between $A_o$ and $M_H$ for the S0's? As it will be shown in the following, the Virgo cluster S0's are H I deficient and therefore they would have to be considered separately here; but, in fact, due to the very high proportion of non-detections, it is impossible to determine any $(A_o, M_H)$ relation for them; therefore we shall limit the search of such a relation to the non-cluster S0's only. Figure 2 presents the corresponding plot; because of the low proportion of detections, the searched relation cannot be derived directly; however, it is possible to derive it using out statistical method (Chamaraux, 1986). For this we bin the range of the $A_o$-values in several relatively small intervals; our method allows to compute the average $M_H$-value in each of them, hence the regression $\overline{M_H(A_o)}$. Of course, we have first to show that the condition of application of the method is fulfilled for such a treatment, i.e. that the distribution of the $M_{H_l}$ values for the galaxies having a given $M_H$ does not depend on $M_H$ (see Sect. 2).

**Table 1.** Data for the S0's of the sample. *Col. 1*: Name of the galaxy: N for NGC, I for IC. *Col. 2*: RC2 numerical morphological type. *Col. 3*: RC2 weight for the type. *Col. 4*: Morphological type from Sandage and Tammann (1981). *Col. 5*: RC2 apparent major diameter in arcmin to surface brightness level 25 m/□″ corrected to "face-on" view and for galactic extinction. *Col. 6*: Lowest detectable H I flux (in Jy km s$^{-1}$) in the Arecibo observation of the galaxy in its central position. *Col. 7*: H I flux detected in the Arecibo observation at the central position of the galaxy. *Col. 8*: References for the Arecibo observations. (1) Bieging & Biermann (1977); (2) Biermann et al. (1979); (3) Chamaraux et al. (1986); (4) Giovanardi et al. (1983); (5) Haynes (1981); (6) Knapp et al. (1979); (7) Krumm & Salpeter (1979a). *Col. 9*: Correction factor for Arecibo beam filling computed as described in the text; underlined numbers correspond to galaxies for which total H I fluxes are known; they are determined directly from total and central H I fluxes. *Col. 10*: Minimum value of the H I mean surface density allowing the detection of the galaxy in the corresponding Arecibo central observation (beam-filling accounted for). *Col. 11*: H I mean surface density of the galaxy after correction for beam filling. Underlined values are directly computed from measured H I total fluxes; references for those measurements are: (a) Balkowski & Chamaraux (1983); (b) Burstein & Krumm (1981); (c) Chamaraux et al. (1986); (d) Helou et al. (1982); (e) Huchtmeier (1982); (f) Krumm & Salpeter (1979b); (g) Peterson (1979). *Col. 12*: Distance of the galaxy in Mpc computed with $H_o = 100$ km s$^{-1}$ Mpc$^{-1}$; for the Virgo cluster, a distance of 16.8 Mpc has been adopted (Tully & Shaya, 1984). *Col. 13*: Linear diameter in kpc corresponding to the apparent one given in column 5. *Col. 14*: H I mass of the galaxy (or its upper limit) in $10^8 M_\odot$. *Col. 15*: Cluster membership: V for Virgo cluster; V ext for Virgo extension, Peg for Pegasus I cluster.

| Galaxy 1 | $T_{dV}$ 2 | w 3 | $T_{ST}$ 4 | $a_o$ (′) 5 | $F_{H_{1c}}$ (Jy km s$^{-1}$) 6 | $F_{H_c}$ (Jy km s$^{-1}$) 7 | Ref 8 | $f_c$ 9 | $\sigma_{H_1}$ ($10^{-3}$ g cm$^{-2}$) 10 | $\sigma_H$ ($10^{-3}$ g cm$^{-2}$) 11 | D (Mpc) 12 | $A_o$ (kpc) 13 | $M_H$ ($10^8 M_\odot$) 14 | Cluster 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N 16 | -3 | 3.2 | S0 | 2.0 | 0.8 | | 4 | 1.62 | 0.241 | | 32.7 | 19.0 | <3.27 | |
| N 80 | -3 | 2.3 | | 2.7 | 2.1 | | 3 | 2.65 | 0.568 | | 59.1 | 46.3 | <45.9 | |
| N 128 | -2 | 4.0 | S0 | 2.8 | 1.4 | | 3 | 1.85 | 0.252 | | 43.8 | 35.1 | <11.7 | |
| N 160 | -1 | 3.6 | | 3.0 | 1.3 | 3.56 | 3 | 2.45 | 0.257 | 0.705 | 54.6 | 48.0 | 61.3 | |
| N 315 | -3 | 2.4 | | 3.2 | 1.4 | | 3 | 2.86 | 0.283 | | 51.3 | 48.3 | <24.8 | |
| N 379 | -2 | 3.4 | | 1.7 | 2.2 | | 1 | 1.45 | 0.820 | | 57.6 | 28.5 | <24.9 | |
| N 383 | -3 | 3.8 | | 2.5 | 1.5 | | 3 | 2.29 | 0.421 | | 52.8 | 37.7 | <22.6 | |
| I 89 | -2 | 2.2 | | 2.3 | 1.0 | 1.07 | 3 | 2.13 | 0.285 | 0.306 | 55.6 | 37.9 | 16.6 | |
| N 467 | -2 | 4.2 | | 2.6 | 1.6 | | 3 | 2.61 | 0.468 | | 55.7 | 41.7 | <30.5 | |
| N 474 | -2 | 4.9 | S0/a | 8.3 | 1.3 | | 5 | 16.78 | 0.235 | | 24.4 | 59.0 | <30.5 | |
| N 499 | -3 | 2.1 | | 2.1 | 1.2 | | 3 | 1.92 | 0.373 | | 45.7 | 28.5 | <11.4 | |
| N 524 | -1 | 4.4 | S0/Sa | 3.5 | 0.72 | | 2 | 3.94 | 0.173 | | 25.5 | 25.7 | <4.37 | |
| N 661 | -2 | 2.2 | | 2.3 | 0.57 | | 3 | 2.08 | 0.166 | | 40.1 | 26.7 | <4.49 | |
| N 670 | -2 | 2.0 | Sb: | 2.3 | 0.85 | 3.9 | 4 | 1.73 | 0.207 | 0.947 | 38.7 | 25.8 | 23.9 | |
| N 890 | -3 | 3.5 | S0 | 2.9 | 0.9 | | 3 | 2.40 | 0.192 | | 42.0 | 35.3 | <8.98 | |
| N1167 | -3 | 2.5 | | 3.5 | 1.4 | 4.36 | 3 | 2.64 | 0.227 | 0.707(c) | 50.9 | 51.4 | 70.4 | |
| N2562 | -1 | 1.7 | | 1.4 | 1.59 | | 2 | 1.35 | 0.831 | | 46.6 | 19.0 | <11.3 | Cancer |
| N2563 | -2 | 2.2 | | 2.4 | 0.55 | | 3 | 2.11 | 0.150 | | 46.6 | 32.5 | <5.96 | Cancer |
| N2577 | -3 | 2.0 | | 2.1 | 1.0 | | 1 | 1.73 | 0.293 | | 20.3 | 12.3 | <1.68 | |
| N2764 | -2 | 1.8 | Am or Sb | 1.7 | 0.85 | 4.6 | 4 | 1.45 | 0.330 | 1.78 | 26.2 | 12.6 | 10.74 | |
| N2765 | -2 | 2.1 | | 2.3 | 1.3 | | 4 | 1.83 | 0.336 | | 36.4 | 24.3 | <7.45 | |
| N2859 | -1 | 4.7 | S0 | 5.0 | 0.85 | 1.17 | 1,4 | 6.48 | 0.162 | 0.220 | 16.8 | 24.5 | 5.05 | |
| N2911 | -2 | 3.9 | S0 | 4.3 | 0.7 | 3.1 | 3 | 1.81 | 0.057 | 0.227(c) | 30.6 | 37.9 | 12.4 | |
| N2962 | -1 | 3.7 | S0 | 3.2 | 0.85 | 3.5 | 4 | 2.93 | 0.176 | 0.724 | 17.9 | 16.8 | 7.71 | |
| N3032 | -2 | 4.1 | S0/Sa | 2.5 | 0.85 | 1.1 | 1,4 | 5.44 | 0.544 | 0.702(g) | 14.8 | 10.8 | 3.10 | |
| N3098 | -2 | 3.1 | S0 | 2.1 | 0.7 | | 4 | 1.51 | 0.180 | | 13.2 | 8.0 | <0.438 | |
| N3156 | -2 | 2.8 | E5: | 2.0 | 0.7 | | 4 | 1.63 | 0.212 | | 11.2 | 6.5 | <0.342 | |
| N3222 | -2 | 1.8 | | 1.4 | 1.5 | | 2 | 1.40 | 0.815 | | 54.9 | 22.0 | <14.8 | |
| N3245 | -2 | 3.6 | S0 | 3.1 | 0.36 | | 1 | 2.46 | 0.069 | | 13.1 | 11.8 | <0.369 | |
| N3300 | -2 | 3.2 | S0 | 1.7 | 0.7 | | 4 | 1.44 | 0.258 | | 28.7 | 14.2 | <1.96 | |
| N3384 | -3 | 4.6 | S0 | 5.2 | 0.8 | | 4 | 4.33 | 0.091 | | 6.0 | 9.2 | <0.294 | |
| N3412 | -2 | 3.7 | S0 | 3.4 | 0.56 | | 1 | 2.72 | 0.098 | | 7.4 | 7.3 | <0.199 | |
| N3413 | -2 | 3.2 | | 3.8 | 0.7 | 10.3 | 3 | 1.49 | 0.050 | 0.782(c,d) | 6.2 | 6.8 | 1.37 | |
| N3414 | -2 | 4.1 | S0 | 3.6 | 1.0 | 1.0 | 1 | 3.48 | 0.195 | 0.195 | 13.1 | 13.8 | 1.39 | |
| N3489 | -1 | 3.7 | S0/Sa | 3.4 | 0.6 | 0.6 | 4 | 1.65 | 0.107 | 0.107 | 5.9 | 5.8 | 0.135 | |
| N3599 | -2 | 3.7 | | 3.0 | 0.6 | | 4 | 3.18 | 0.162 | | 7.6 | 6.5 | <0.258 | |
| N3607 | -2 | 3.4 | S0 | 3.8 | 1.8 | | 2 | 4.16 | 0.382 | | 8.6 | 9.5 | <1.30 | |
| N3626 | -1 | 3.6 | Sa | 3.0 | 3.6 | 5.5 | 7 | 3.35 | 0.971 | 1.507(e) | 13.5 | 12.2 | 7.96 | |
| N3630 | -2 | 2.7 | S0 | 2.0 | 0.61 | | 1 | 1.52 | 0.171 | | 13.6 | 7.9 | <0.410 | |
| N3773 | -2 | 3.2 | pec | 1.7 | 1.4 | 2.6 | 6 | 1.59 | 0.598 | 1.11 | 8.7 | 4.2 | 0.731 | |
| N3801 | -2 | 2.4 | | 3.0 | 0.85 | 2.2 | 4 | 2.39 | 0.172 | 0.446 | 31.6 | 27.1 | 12.4 | |
| N3900 | -1 | 3.2 | Sa | 3.2 | 1.3 | | | 2.50 | 0.240 | 1.596(a,e) | 16.7 | 15.3 | 14.1 | |
| N3941 | -2 | 3.3 | S0/a | 3.7 | 1.1 | 4.9 | 1 | 4.21 | 0.248 | 1.103(e) | 9.7 | 10.5 | 4.55 | |
| N3986 | -2 | 3.2 | | 2.4 | 1.3 | 3.52 | 3 | 1.21 | 0.202 | 0.546(c) | 32.6 | 22.7 | 10.7 | |
| N4073 | -3 | 2.2 | E5 | 2.5 | 1.2 | | 3 | 2.19 | 0.321 | | 58.3 | 41.6 | <21.0 | |
| N4124 | -1 | 3.7 | S0 | 3.8 | 0.5 | | 4 | 2.65 | 0.069 | | 16.8 | 18.6 | <0.898 | V |
| N4150 | -2 | 3.4 | S0/Sa | 2.5 | 0.45 | | 6 | 2.12 | 0.117 | | 2.4 | 1.7 | <0.0125 | |
| N4179 | -2 | 3.1 | S0 | 3.4 | 1.4 | | 4 | 2.19 | 0.197 | | 16.8 | 16.6 | <2.04 | V ext |
| N4203 | -3 | 3.9 | S0 | 3.9 | 1.1 | 6.6 | 1 | 4.09 | 0.221 | 1.318(b) | 10.9 | 12.3 | 7.48 | |
| N4215 | -1 | 3.0 | S0 | 1.7 | 1.2 | | 4 | 1.37 | 0.440 | | 16.8 | 8.3 | <1.14 | V ext |
| N4233 | -1 | 2.0 | S0 | 2.1 | 0.52 | | 3 | 1.64 | 0.137 | | 16.8 | 10.3 | <0.547 | V |
| N4251 | -2 | 3.3 | S0 | 3.7 | 0.56 | | 1 | 2.74 | 0.082 | | 10.0 | 10.8 | <0.356 | |
| N4262 | -3 | 4.1 | S0 | 2.3 | 1.1 | 4.5 | 1 | 1.99 | 0.308 | 1.259(f) | 16.8 | 11.2 | 5.94 | V |
| N4267 | -3 | 3.9 | S0 | 3.6 | 0.8 | | 4 | 4.08 | 0.183 | | 16.8 | 17.6 | <2.13 | V |
| N4270 | -2 | 2.7 | S0 | 1.9 | 2.9 | | 7 | 1.50 | 0.886 | | 16.8 | 9.3 | <2.88 | V ext |
| N4281 | -1 | 3.0 | S0 | 2.8 | 3.0 | | 7 | 2.10 | 0.586 | | 16.8 | 13.7 | <4.14 | V ext |
| N4292 | -2 | 2.0 | | 2.0 | 1.9 | | 3 | 1.72 | 0.579 | | 16.8 | 9.8 | <2.09 | V ext |

**Table 1** (continued)

| Galaxy | $T_{dV}$ | w | $T_{ST}$ | $a_o$ | $F_{H_{lc}}$ | $F_{H_c}$ | Ref | $f_c$ | $\sigma_{H_l}$ | $\sigma_H$ | D | $A_o$ | $M_H$ | Cluster |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N4309 | -1 | 3.2 | | 1.9 | 0.66 | | 3 | 1.58 | 0.212 | | 16.8 | 9.3 | <0.690 | V |
| N4310 | -1 | 2.1 | | 2.3 | 0.7 | 1.15 | 3 | 1.85 | 0.173 | 0.286 | 9.0 | 6.2 | 0.407 | |
| N4324 | -1 | 3.3 | | 2.2 | 3.4 | 3.4 | 7 | 3.26 | 1.637 | 1.637(e) | 16.8 | 10.8 | 7.18 | V ext |
| N4340 | -1 | 3.5 | S0 | 4.0 | 0.6 | | 4 | 4.17 | 0.117 | | 16.8 | 19.6 | <1.69 | V |
| N4344 | -2 | 2.1 | | 2.0 | 0.85 | 1.2 | 4 | 1.95 | 0.295 | 0.416 | 16.8 | 9.8 | 1.50 | V |
| N4350 | -2 | 2.9 | S0 | 2.7 | 0.7 | | 4 | 1.87 | 0.132 | | 16.8 | 13.2 | <0.865 | V |
| N4352 | -2 | 1.8 | | 1.7 | 0.8 | | 4 | 1.43 | 0.279 | | 16.8 | 8.3 | <0.723 | V |
| N4371 | -1 | 4.4 | S0 | 3.6 | 0.7 | | 4 | 3.15 | 0.123 | | 16.8 | 17.6 | <1.43 | V |
| N4377 | -3 | 2.8 | S0 | 1.9 | 0.8 | | 4 | 1.73 | 0.296 | | 16.8 | 9.3 | <0.963 | V |
| N4379 | -3 | 2.2 | S0 | 2.1 | 0.9 | | 4 | 2.00 | 0.292 | | 16.8 | 10.3 | <1.17 | V |
| N4382 | -1 | 5.0 | S0 | 6.9 | 0.7 | | 4 | 9.91 | 0.109 | | 16.8 | 33.7 | <4.66 | V |
| N4385 | -1 | 2.9 | Sbc | 2.2 | 3.6 | 4.5 | 7 | 1.04 | 0.555 | 0.694(f) | 16.8 | 10.8 | 3.04 | V ext |
| N4417 | -2 | 2.3 | S0 | 3.2 | 0.7 | | 4 | 2.21 | 0.115 | | 16.8 | 15.6 | <1.05 | V |
| N4425 | -2 | 2.2 | S0 or Sa | 2.8 | 0.6 | | 4 | 1.94 | 0.109 | | 16.8 | 13.7 | <0.769 | V |
| N4429 | -1 | 4.6 | S0/Sa | 4.9 | 0.8 | | 4 | 4.02 | 0.101 | | 16.8 | 24.0 | <2.19 | V |
| N4435 | -2 | 3.6 | S0 | 2.9 | 0.6 | | 4 | 2.42 | 0.128 | | 16.8 | 14.2 | <0.971 | V |
| N4442 | -2 | 3.3 | S0 | 4.1 | 0.7 | | 4 | 3.01 | 0.093 | | 16.8 | 20.0 | <1.40 | V |
| N4451 | -2 | 1.8 | | 1.5 | 0.85 | 2.4 | 4 | 1.40 | 0.403 | 1.14 | 16.8 | 7.3 | 2.29 | V |
| N4459 | -1 | 3.8 | S0 | 3.7 | 1.2 | | 4 | 3.59 | 0.230 | | 16.8 | 18.1 | <2.83 | V |
| N4461 | -1 | 3.6 | Sa | 3.2 | 0.7 | | 4 | 2.29 | 0.112 | | 16.8 | 15.6 | <1.03 | V |
| N4474 | -2 | 2.0 | S0 | 2.2 | 1.1 | | 4 | 1.71 | 0.291 | | 16.8 | 10.8 | <1.28 | V |
| N4476 | -3 | 3.8 | E | 1.9 | 0.8 | | 4 | 1.61 | 0.276 | | 16.8 | 9.3 | <0.898 | V |
| N4477 | -2 | 4.0 | S0/Sa | 4.2 | 0.6 | | 4 | 4.88 | 0.127 | | 16.8 | 20.5 | <2.01 | V |
| N4479 | -2 | 3.2 | | 1.9 | 0.8 | | 4 | 1.71 | 0.293 | | 16.8 | 9.3 | <0.953 | V |
| N4503 | -3 | 3.2 | Sa | 3.2 | 0.6 | | 4 | 2.45 | 0.103 | | 16.8 | 15.6 | <0.943 | V |
| N4515 | -3 | 1.9 | | 1.6 | 0.6 | | 4 | 1.56 | 0.264 | | 16.8 | 7.8 | <0.604 | V |
| N4526 | -2 | 3.6 | S0 | 5.9 | 0.63 | | 6 | 4.30 | 0.056 | | 16.8 | 28.8 | <1.75 | V |
| N4528 | -3 | 1.9 | | 1.8 | 0.7 | | 4 | 1.54 | 0.253 | | 16.8 | 8.8 | <0.737 | V |
| N4550 | -1 | 2.1 | E/S0 | 2.8 | 1.4 | | 6 | 1.85 | 0.252 | | 16.8 | 13.7 | <1.78 | V |
| N4570 | -2 | 4.1 | S0/E | 3.3 | 0.6 | | 4 | 2.18 | 0.087 | | 16.8 | 16.1 | <0.848 | V |
| N4578 | -2 | 2.6 | S0 | 3.6 | 0.5 | | 4 | 3.53 | 0.099 | | 16.8 | 17.6 | <1.15 | V |
| N4596 | -1 | 3.8 | Sa | 3.9 | 0.9 | | 4 | 3.78 | 0.166 | | 16.8 | 19.1 | <2.28 | V |
| N4608 | -2 | 3.7 | S0/a | 3.2 | 0.8 | | 4 | 3.19 | 0.179 | | 16.8 | 15.6 | <1.64 | V |
| N4612 | -2 | 4.0 | S0 | 2.2 | 0.7 | | 4 | 2.05 | 0.211 | | 16.8 | 10.8 | <0.926 | V |
| N4620 | -2 | 2.1 | | 2.1 | 0.48 | | 3 | 2.02 | 0.158 | | 16.8 | 10.3 | <0.630 | V |
| N4623 | -1 | 2.0 | E | 2.2 | 3.4 | | 7 | 1.59 | 0.835 | | 16.8 | 10.8 | <3.66 | V |
| N4638 | -3 | 2.6 | S0 | 2.7 | 0.8 | | 4 | 2.12 | 0.174 | | 16.8 | 13.2 | <1.14 | V |
| N4694 | -2 | 3.6 | Am | 3.2 | 0.85 | 2.9 | 4 | 2.05 | 0.123 | 0.420(f) | 16.8 | 15.6 | 3.84 | V |
| N4710 | -1 | 3.7 | S0 | 3.9 | 1.8 | | 2 | 2.47 | 0.217 | | 16.8 | 19.1 | <2.98 | V |
| N4715 | -1 | 2.1 | | 2.0 | 1.1 | | 3 | 1.91 | 0.367 | | 69.5 | 40.4 | <22.5 | Coma |
| N4733 | -3 | 2.3 | | 2.5 | 0.7 | | 4 | 2.38 | 0.204 | | 16.8 | 12.2 | <1.14 | V |
| N4754 | -3 | 3.9 | S0 | 4.4 | 0.8 | | 4 | 3.75 | 0.116 | | 16.8 | 21.5 | <2.02 | V |
| N4762 | -2 | 4.0 | S0 | 6.3 | 0.33 | | 1 | 3.84 | 0.023 | | 16.8 | 30.8 | <0.821 | V |
| N4849 | -3 | 2.1 | | 2.2 | 0.53 | | 3 | 1.93 | 0.158 | | 69.5 | 44.5 | <11.8 | Coma |
| N4866 | -1 | 3.8 | Sa | 4.8 | 0.85 | 8.3 | 4 | 2.67 | 0.072 | 0.716(d) | 16.8 | 23.5 | 14.9 | V ext |
| N4914 | -3 | 2.5 | S0 | 3.5 | 1.3 | | 3 | 2.89 | 0.231 | | 69.5 | 70.8 | <43.5 | Coma |
| N4931 | -2 | 1.8 | | 1.7 | 0.54 | | 3 | 1.38 | 0.190 | | 69.5 | 34.4 | <8.46 | Coma |
| N5273 | -2 | 4.3 | S0/a | 3.2 | 0.79 | | 1 | 3.29 | 0.184 | | 11.6 | 10.9 | <0.823 | |
| N5380 | -3 | 2.2 | S0 | 2.3 | 1.3 | | 3 | 2.31 | 0.423 | | 32.6 | 21.7 | <7.51 | |
| N5444 | -3 | 2.4 | E3 | 2.8 | 0.72 | | 3 | 2.74 | 0.183 | | 40.5 | 33.2 | <7.65 | |
| N5574 | -3 | 3.0 | S0 | 1.5 | 0.7 | | 4 | 1.39 | 0.300 | | 15.5 | 7.0 | <0.556 | |
| N5838 | -3 | 3.2 | S0 | 3.7 | 0.93 | | 1 | 2.58 | 0.129 | | 14.3 | 15.4 | <1.16 | |
| N5854 | -1 | 3.2 | Sa | 2.2 | 1.3 | | 4 | 1.59 | 0.305 | | 16.3 | 10.6 | <1.30 | |
| N5864 | -2 | 3.2 | Sa | 2.4 | 0.54 | | 3 | 1.69 | 0.117 | | 18.6 | 13.0 | <0.744 | |
| N6587 | -3 | 2.3 | | 2.9 | 0.36 | | 3 | 3.08 | 0.099 | | 32.1 | 26.9 | <2.68 | |
| N6710 | -1 | 2.0 | | 2.2 | 0.7 | 0.81 | 3 | 1.81 | 0.186 | 0.215 | 48.0 | 31.3 | 7.95 | |
| N7280 | -2 | 2.2 | | 2.5 | 1.0 | 1.06 | 3 | 2.08 | 0.255 | 0.270 | 20.9 | 14.9 | 2.27 | |
| N7332 | -2 | 4.1 | S0 | 3.5 | 1.4 | | 5 | 2.32 | 0.190 | | 16.0 | 16.5 | <1.95 | |
| N7386 | -2 | 2.1 | | 2.2 | 0.45 | | 3 | 2.05 | 0.135 | | 74.2 | 48.3 | <12.0 | |
| N7457 | -3 | 4.4 | S0 | 4.3 | 0.54 | | 6 | 3.68 | 0.081 | | 7.9 | 9.8 | <0.291 | |
| N7550 | -3 | 3.5 | | 1.8 | 0.54 | | 3 | 1.77 | 0.215 | | 53.4 | 28.3 | <6.43 | |
| N7623 | -1 | 2.0 | | 1.9 | 0.72 | | 3 | 1.65 | 0.252 | | 39.9 | 22.1 | <4.63 | Peg |
| N7634 | -2 | 1.8 | | 1.5 | 0.9 | | 4 | 1.43 | 0.434 | | 39.9 | 17.4 | <4.94 | Peg |
| N7648 | -2 | 2.0 | | 1.8 | 0.42 | 0.42 | 3 | 1.58 | 0.148 | 0.148 | 39.9 | 20.9 | 2.43 | Peg |
| N7743 | -1 | 4.3 | Sa | 3.2 | 0.4 | 0.4 | 4 | 11.76 | 0.352 | 0.352(a, e) | 19.0 | 17.5 | 4.00 | |

Now: $M_{H_l} \propto F_{H_l} D^2$ where $D$ is the distance of the galaxy. $F_{H_l}$ depends only on the instrument and is obviously independent of $M_H$. Then the condition is that $M_H$ and $D$ are independent for the galaxies of our sample. This cannot be checked directly, since $M_H$ is unknown for the majority of our sample galaxies. But it is legitimate to make the assumption that $M_H$ depends mainly on $A_o$ (see Fig. 2); then the searched condition is that $A_o$ and $D$ are independent, or that $a_o$ and $A_o$ are independent. Figure 3 shows that this condition is well satisfied for our sample of non-cluster S0's.

In practice, we have applied the method dividing the $A_o$-range into 3 intervals: $A_o \leq 12$ kpc, $12\,\mathrm{kpc} < A_o \leq 24$ kpc, and $A_o > 24$ kpc. The $M_H$-distribution can be determined for only ~60% of the objects in each $A_o$-interval, namely those having the highest H I contents; so one cannot compute $\overline{M_H(A_o)}$. Therefore we have determined instead the median values $\langle M_H(A_o) \rangle$, which are shown on Fig. 2 with their associated uncertainties (method uncertainty plus sample uncertainty); the best straight line passing through the three corresponding points (taking the uncertainties into account) has a slope: $\alpha = 2.1 \pm 0.2$. Thus $\sigma_H$ characterizes very well the H I contents of the S0's.

Note that $M_H/L$ was another possible choice, which we have not adopted because for S0's one has rather $M_H \propto L^{1.2}$, indicating that $M_H/L$ depends slightly on $L$. However the use of our

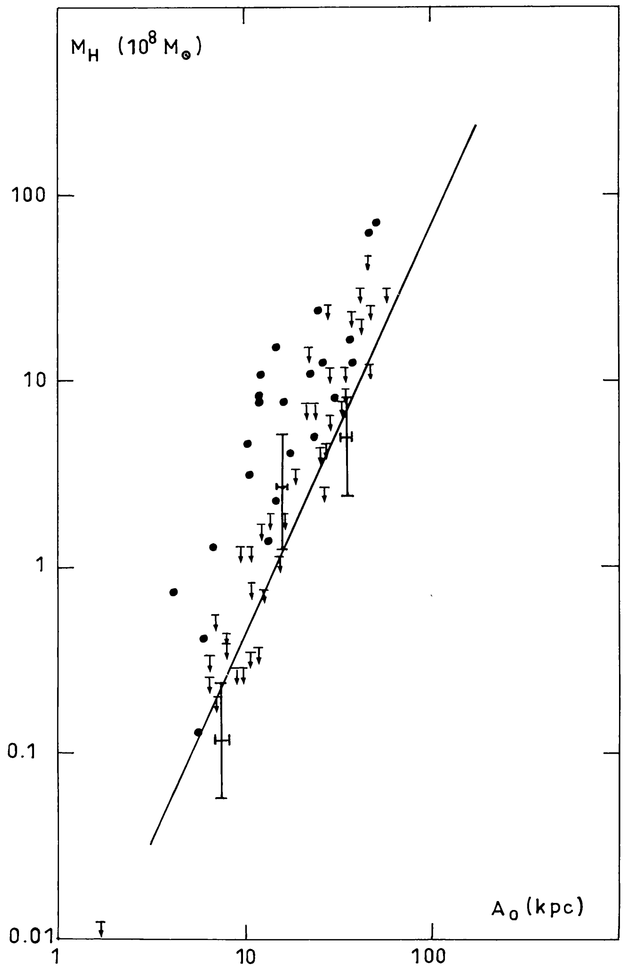

**Fig. 2.** Plot of the H I mass versus the linear diameter for the 62 S0 galaxies of our sample located out of any cluster. The 3 points with error bars represent the median values $\langle M_H \rangle$ for the galaxies having $A_o \leq 12$ kpc, 12 kpc $< A_o \leq 24$ kpc and $A_o > 24$ kpc, respectively. We have drawn the best regression line $M_H(A_o)$ passing through these 3 points, when taking the uncertainties into account; its slope is $2.1 \pm 0.2$

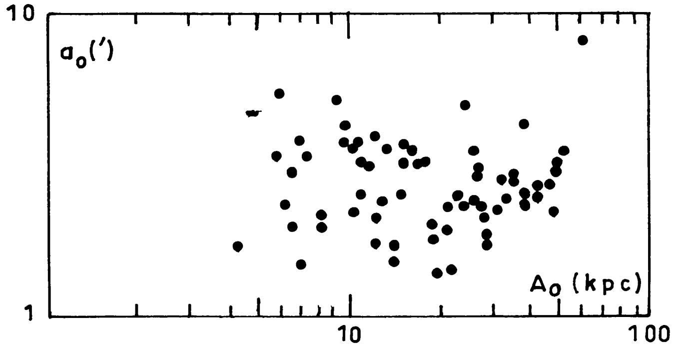

**Fig. 3.** Plot of the apparent diameter $a_o$ versus the linear one $A_o$ for the S0's of our sample belonging neither to the Virgo cluster nor to its extension

statistical method with $M_H/L$ as the H I parameter leads essentially to the same results.

4.1.2 Can our statistical method be used to derive the $\sigma_H$-distribution of the S0's of our sample?

As seen above, the condition of applicability of the method to the $\sigma_H$'s is that the distribution of the $\sigma_{H_I}$'s for the galaxies having a given $\sigma_H$-value does not depend on $\sigma_H$. Since $\sigma_{H_I} \propto F_{H_I}/a_o^2$, this implies that $a_o$ and $\sigma_H$ are independent; let us assume as hereabove that $M_H$ depends mainly on $A_o$. Then we have two cases:

a) The S0's members of the Virgo cluster; these objects are at the same distance from us, so $a_o \propto A_o$ for them. Then the condition is that $A_o$ and $\sigma_H$ are independent. We have just shown that this condition is fulfilled for the non-cluster S0's. It seems reasonable to think that it is also fulfilled for the Virgo cluster S0's, despite their low H I contents, as it is for the Virgo H I deficient late type spirals (Chamaraux et al., 1980).

b) The non-cluster S0's; as shown in Fig. 3, $a_o$ and $A_o$ are independent for the sample of non-cluster S0's. Thus the condition of application of the method is fulfilled, and would remain fulfilled even if $\sigma_H$ depended significantly on $A_o$.

Now we turn to the examination of the distributions of the H I contents of our total sample of S0's, then of the S0's located out of any cluster and finally of the S0's located in the Virgo Cluster.

### *4.2. Study of the total sample*

The application of our statistical method to the total sample of S0's leads to the real distribution of the $\sigma_H$ values shown in Fig. 4. Because of the very large range of the $\sigma_H$ values, $\log \sigma_H$

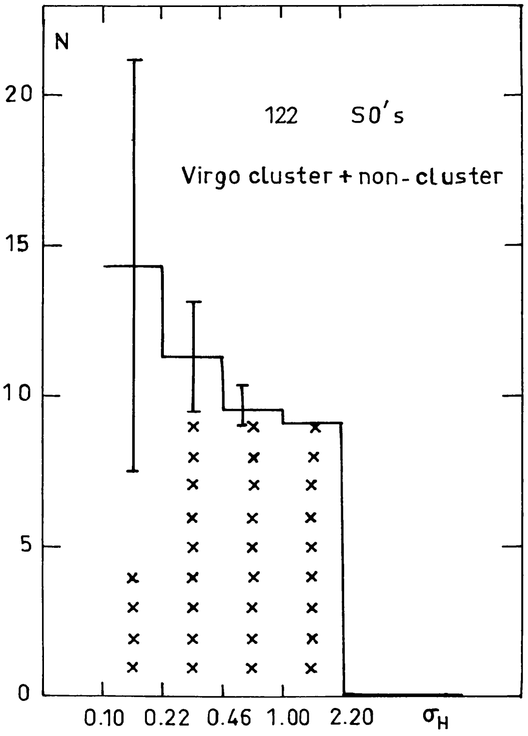

**Fig. 4.** True absolute distribution of the H I mean surface densities $\sigma_H$ (expressed in $10^{-3}$ g cm$^{-2}$) for the objects of the total sample of 122 S0's having $\sigma_H \geq 0.10\ 10^{-3}$ g cm$^{-2}$. Detected galaxies are denoted by crosses; the uncertainties coming from the statistical method are indicated

instead of $\sigma_H$ has been used as a variable, and binned in intervals of width $\frac{1}{3}$; in each interval, the correction factor to derive the true distribution has been computed at the midpoint, just as explained in the previous section. No significant information about the $\sigma_H$ distribution can be obtained for $\sigma_H < 0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$, because of the very low number of non-detections (only 4) in this region. In all the following, this value of $0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$ will represent the limit below which the shape of the $\sigma_H$ distribution of S0's is unknown (note that hereafter, $\sigma_H$ will be implicitly expressed in units of $10^{-3}\,\mathrm{g\,cm^{-2}}$). The statistical uncertainty related to the method is indicated for each point of the histogram; it is large in the first interval only.

The examination of Fig. 4 shows that the distribution of the mean H I surface densities of the S0's is almost flat in the interval of $\sigma_H$ concerned. The histogram also shows that 64% (±6%) of the S0's have $\sigma_H < 0.10$ and 36% have $\sigma_H \geq 0.10$. Note that in the region $\sigma_H \geq 0.10$, only 70% of the S0's are detected, the undetected S0's having probably too small apparent diameters to be detectable.

The mean value of $\sigma_H$ cannot be determined since only a part of the distribution is known; however one can remark that the median value $\langle\sigma_H\rangle$ is lower than 0.10; if the distribution of $\log\sigma_H$ is symmetrical, this upper limit holds also for the mean value.

No further comments will be made about the distribution of the H I contents of the S0's of the whole sample. Indeed after Krumm and Salpeter (1979b) and Giovanardi et al. (1983), it is known that the S0's within the Virgo cluster contain less H I than the ones located out of it, since their detection rate is much lower inside the cluster. Therefore, before pursuing the analysis further on, it is absolutely necessary to treat separately the cluster and the non-cluster S0's of our sample.

### *4.3. S0 galaxies located out of any cluster*

Among the 122 S0's of our whole sample, 43 are members of the Virgo cluster proper; in addition, 8 are located in the so-called Virgo extension or in the immediate vicinity of the main cluster, 4 are members of the Coma cluster, 2 belong to the Cancer cluster and 3 to the Pegasus 1 cluster. It is not known whether the H I deficiency observed in the S0's located within the Virgo cluster is also present in the ones belonging to the Virgo extension and to other clusters as well. In fact, including or excluding the 17 objects located in clusters other than Virgo does not alter our results significantly. However, in order to deal with a pure non-cluster reference sample, we have preferred to remove them. So we are left with the "non-cluster sample", comprising 62 S0's isolated or located in small groups.

#### 4.3.1. The distribution of the mean H I surface density

The $\sigma_H$ distribution for the non-cluster S0's is presented in Fig. 5 for $\sigma_H \geq 0.10$. Now there is a clearer indication of an increase of the distribution at $\sigma_H \sim 0.15$; on the other hand, as expected, the proportion of S0's having $\sigma_H \geq 0.10$ is higher than for the whole sample, being now 60% ± 14%, a relatively high value. This result and the shape of the distribution show in particular that, as it has been found for the ellipticals by Knapp et al. (1985), there is no evidence in the non-cluster S0's either of a majority of objects having very little gas if any, or of two distinct populations having completely different H I contents.

The median value of $\log\sigma_H$ for non-cluster S0's is: $\langle\log\sigma_H\rangle = -0.87 \pm 0.10$, i.e., $\langle\sigma_H\rangle = 0.13$ within a factor of 1.3, the uncertainty coming from our statistical method. If the distribution of $\log\sigma_H$ is symmetrical, then the mean $\overline{\log\sigma_H}$ is also $-0.87$. This would imply that the S0's have on average an H I content 5 times lower than the S0/a spirals and 10 times lower than the Sa (see next section for the detailed computation of $\sigma_H$ for early spirals). Under the same assumption of symmetry of the $\log\sigma_H$-distribution, its dispersion $\sigma$ can also be computed; we find $\sigma = 0.61$ (i.e. a factor of 4 on $\sigma_H$), much higher than the values ~0.2, 0.3 and 0.4 found respectively for spiral later than Sb (Balkowski, 1973), Sa and S0/a (see next section). Note also that if the assumption of symmetry is verified, it implies that a few S0's have $\sigma_H$ as low as 0.01 or even less, thus extremely low H I masses $\sim 10^7\,M_\odot$.

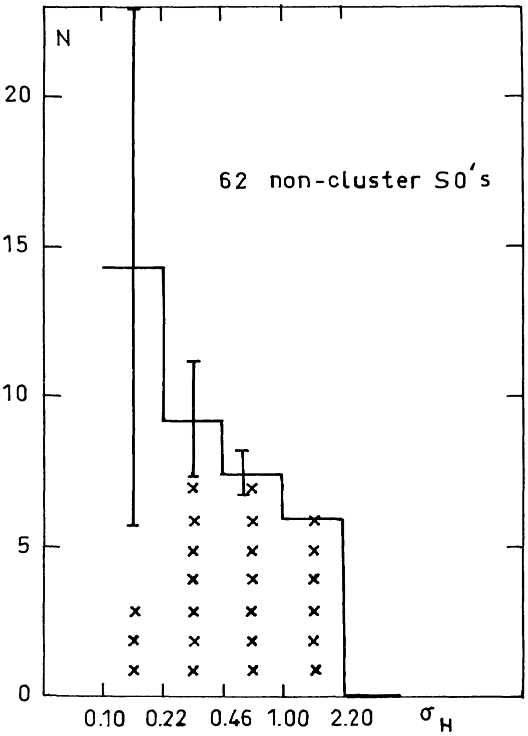

**Fig. 5.** Distribution of the $\sigma_H$ expressed in $10^{-3}\,\mathrm{g\,cm^{-2}}$ for the objects belonging to the sample of 62 non-cluster S0's and having $\sigma_H \geq 0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$

#### 4.3.2. The problem of the contamination by the spirals

This problem has to be examined seriously, because it is well known that, when observed in optimal conditions some galaxies originally classified as S0's turn out to show faint spiral arms and to be in fact early spirals. Such a contamination would have as main consequence an artificial excess of high $\sigma_H$ values in our $\sigma_H$-distribution, hence also a too high dispersion of $\sigma_H$'s.

Therefore the best way to study this problem of contamination is to use a classification made from deeper plates than the RC2 one. Sandage and Tammann's "Revised Shapley-Ames Catalog of Bright Galaxies" (1981) provides such a classification, mainly carried out from Palomar 5 m telescope plates in the Northern hemisphere. Thirty-nine objects of our non-cluster sample appear in Sandage and Tammann (1981) (hereafter ST). Among them, 21 are classified S0's by ST, 7 S0/Sa, 5 Sa, 2 possible Sb, 1 peculiar and 3 E's (see Table 1). The types of the 7 ST spirals are determined from 5 m Palomar plates, whereas only one of them is classified in the RC2 from such a source. So the disagreement between ST and the RC2 seems to come from the quality of the data, and favours the ST types as the best ones. This is confirmed by the examination of the corrected $\sigma_H$-distribution of these 7 spirals + 1 peculiar; their median value is $\langle\sigma_H\rangle = 1.0$, a typical value for early spirals. Note that 4 galaxies among the 6 of our non-cluster sample having $\sigma_H > 1.0$ are ST spirals, which shows that the contamination affects strongly the highest values of the $\sigma_H$-distribution.

The S0/Sa have not a true spiral structure, and in fact the seven in our sample have $\langle\sigma_H\rangle = 0.14$, not very different from $\langle\sigma_H\rangle \sim 0.10$ for the ST S0's. So grouping them together, we obtain the $\sigma_H$-distribution for the "true" S0's shown in Fig. 6. It differs from the one for RC2 S0's mainly in the region $\sigma_H > 0.2$, where it is substantially lower and flatter than the latter. A difference limited to these $\sigma_H$-values was expected, since most of the early spirals have $\sigma_H > 0.2$ (see Fig. 9). On the other hand, the comparison between the 2 distributions in Fig. 6 shows that the spiral contamination of our total sample is about 20% at most; this is no more than for the ST subsample, despite the fact that the RC2 classification is more uncertain for the objects not classified by ST, which are less bright than the other ones. At last the median $\langle\sigma_H\rangle$ for the "true" S0's distribution is: $\langle\sigma_H\rangle \sim 0.10$, and the proportion of true S0's having $\sigma_H > 0.10$ is: $p = 44\% \pm 13\%$.

Thus the contamination of our sample by the spirals does not affect significantly the two fundamental quantities in our study, namely the average H I content and the proportion of S0's having $\sigma_H > 0.10$. Therefore, since our sample objects are not all classified by ST, we can continue to work with the RC2 classification in the following, only keeping the previous results in mind.

#### 4.3.3. Correlation with the RC2 type

The RC2 considers three morphological types among the S0's, numbered from $-3$ to $-1$, and corresponding to an increasing importance of the dark matter around the nucleus. There is some correlation between this classification and the division between S0 and S0/Sa by ST; indeed, for 24 ST S0/Sa, $\bar{T} = -1.7 \pm 0.2$, and for 152 ST S0's, $\bar{T} = -2.4 \pm 0.1$. So one can expect a variation of the H I contents along the RC2 sequence.

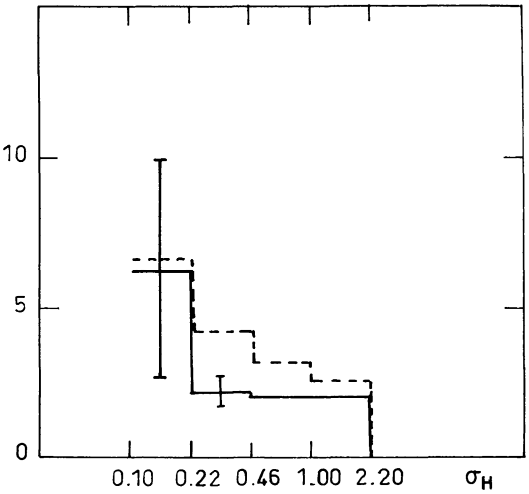

**Fig. 6.** Full line: $\sigma_H$-distribution for the 28 galaxies of our non-cluster S0 sample classified S0's (21 objects) or S0/Sa (7 objects) by Sandage and Tammann (1981). Broken line: $\sigma_H$-distribution for the total non-cluster sample (cf. Fig. 5) but normalized to the same number of objects as the previous histogram

The $\sigma_H$ distributions for each type are shown in Figs. 7a–c and the results are summarized in Table 2. There is an increase of the H I content of more than a factor of 3 when going from $T = -3$ to $-1$. This is a very important increase indeed, which is as high as that observed among the whole sequence of spiral galaxies from Sa to Sm! This result gives a clear physical significance to the de Vaucouleurs' subdivision of S0's based on morphological criteria; it also shows that the origin of at least a part of the large dispersion of the H I contents found for the whole sample of the non-cluster S0's is due to the mixing of types with different $\sigma_H$. Finally this result shows the continuity of the H I global properties along the Hubble sequence from elliptical to irregular galaxies: S0's appear no more different from spirals as far as their gas content is concerned.

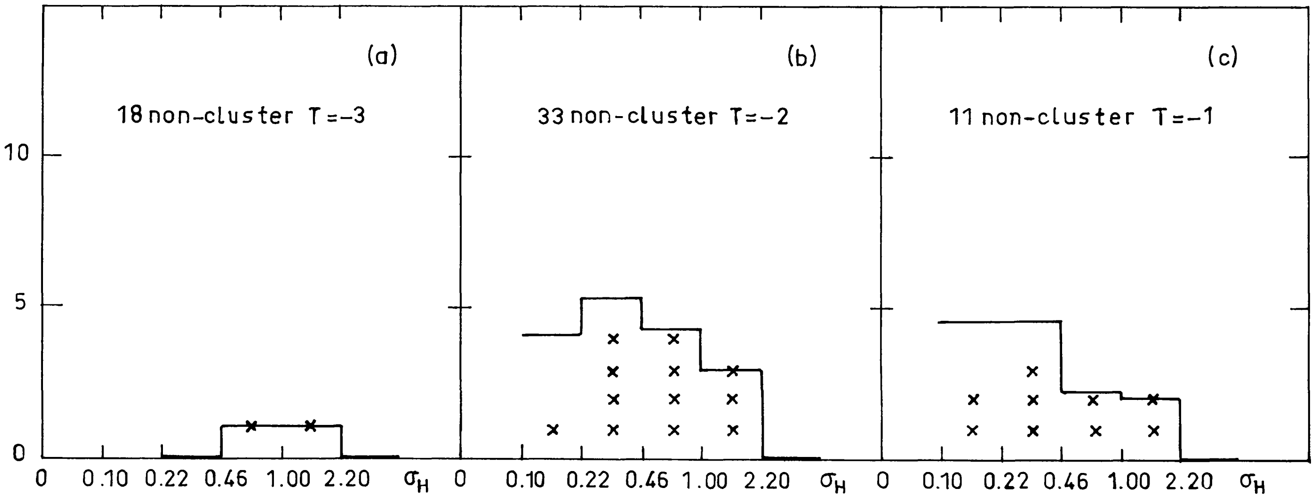

**Fig. 7a–c.** Distributions of the $\sigma_H$ for the non-cluster S0's of RC2 types $-3$, $-2$ and $-1$ respectively and having $\sigma_H \geq 0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$

**Table 2.** H I contents of RC2 S0's of types −3, −2, −1. *Line 1*: RC2 numerical morphological type. *Line 2*: Median value of the mean H I projected density $\sigma_H$ for the different lenticular types. *Line 3*: Percentage of objects having $\sigma_H > 0.10\,10^{-3}\,\mathrm{g\,cm^{-2}}$ in each lenticular type. *Line 4*: Number of galaxies in each lenticular type.

| type / parameter | −3 | −2 | −1 |
|---|---|---|---|
| $\langle\sigma_H\rangle$ med | <0.10 | ~0.10 | 0.34 ± 0.03 |
| % with $\sigma_H > 0.10$ | 11% ± 22% | 15% ± 16% | $94\%^{+6\%}_{-27\%}$ |
| Number of galaxies | 18 | 33 | 11 |

### 4.4. *The S0's located in the Virgo cluster*

Forty three S0's of our sample belong to the Virgo cluster, having redshifts lower than 2500 km s$^{-1}$ and being located at less than 6° from the nominal centre of the cluster at $\alpha = 12^h27^m$, $\delta = +13.^{\circ}5$, as defined by de Vaucouleurs (1961). Only four of them have been detected; among them, NGC 4451 has been unambigously recognized by Sandage et al. (1985) as a spiral galaxy, and therefore has to be removed from our sample (as a matter of fact, its $\sigma_H$ value is 1.1, which is characteristic of a spiral). We are then left with 42 S0's including 3 detections. The true distribution of their $\sigma_H$ is shown in Fig. 8. It differs completely from the one found for the non-cluster galaxies, since only 7% ± 4% among the Virgo S0's have $\sigma_H \geq 0.10$ (instead of 60% for the non-cluster ones), a value clearly indicating a lower H I content.

Before pursuing, we have to check whether the differences in the H I contents are not due to different optical characteristics for Virgo and non-cluster S0's. From what has been shown hereabove, an obvious reason for such a difference could be an excess of types $T = -3$ in the Virgo sample. In fact the proportion of $T = -3$ is the same in Virgo and in the non-cluster sample, and the proportion of $T = -1$ is even higher in Virgo (31% compared to 18% in the non-cluster sample), so a slight H I excess would be expected in Virgo on the basis of the morphological types alone! Note also that the mean apparent and linear diameters are basically the same in the two samples, ruling out any spurious effect related to beam corrections or to the possible dependence of $\sigma_H$ on $A_0$. In fact, the H I contents of Virgo S0's are even probably overestimated when computed with the standard beam correction, since the H I diameters of S0's are expected to be smaller in Virgo than out of it, if they follow the same trend as the spirals (van Gorkom et al., 1984).

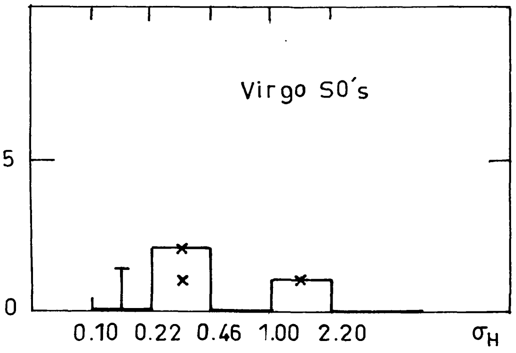

**Fig. 8.** Distribution of the $\sigma_H$ for Virgo cluster S0's having $\sigma_H \geq 0.10\,10^{-3}\,\mathrm{cm^{-2}}$

Thus the Virgo cluster S0's exhibit lower H I contents, although they have the same optical characteristic as the non-cluster S0's. So they are affected by an H I deficiency as well as late type spirals (Chamaraux et al., 1980; Giovanelli and Haynes, 1983). Unfortunately, it is not possible to estimate the amount of deficiency from the poor upper limit $\langle\sigma_H\rangle < 0.10$ obtained for the median of $\sigma_H$ for the Virgo S0's. It is a pity, because this could be a test for the stripping by the intracluster gas as the cause of the H I deficiency. Indeed detailed studies of the spatial distributions of H I in S0's carried out at Westerbork by van Woerden et al. (1983) show that the gas is often concentrated in a narrow ring, having a diameter typically of the order of the optical diameter. Such external rings are obviously very sensitive to stripping, and, if stripping is causing the deficiency, much higher H I deficiencies are expected in the Virgo S0's than in late spirals where H I is more concentrated towards the centre. From van Woerden et al.'s (1983) detailed H I studies, one can also see that the spatial distribution of H I in early spirals is intermediate between what is found in S0's and what is encountered in later spirals. Therefore, as another test for the stripping, we can now study the H I contents of the early spirals in the Virgo cluster.

## 5. The H I deficiency of Virgo cluster early spirals S0/a, Sa and Sab

### 5.1. *The Virgo cluster data*

As a source of H I data for galaxies of types 0, 1, 2 members of the Virgo cluster, we use mainly Arecibo observations, because of the excellent values of the H I flux limits reached; the majority of them have been taken from Giovanardi et al. (1983) and from Helou et al. (1984). The gathered sample contains 26 early spirals members of the Virgo cluster (same membership condition as above) with 14 detections, and 16 galaxies belonging to the Virgo X cloud or to further cluster extensions (13 detections). The galaxies NGC 4224 and NGC 4235, which are members of the small W-clouds, have not been included in the Virgo sample since, according to de Vaucouleurs (1961), these two clouds are not related to the Virgo cluster.

### 5.2. *The beam corrections*

Half of these galaxies have been observed at their central position only, and since their apparent dimensions are not small compared to the Arecibo beamwidth, a correction for beam-smearing has to be applied in order to get the total H I fluxes or their upper limits. The correction procedure is the same as the one adopted hereabove for the S0's, except that the mean value of the ratio $a_H/a_0$ used in this computation is now 1.3, the number obtained by Fouqué (1983) for 21 galaxies of types 0, 1, 2 (the $a_H/a_0$ ratio does not vary significantly between these three types). As for the S0's, we have then checked the validity of the correction using early spirals mapped at Arecibo, or measured at their centres with radiotelescopes having larger beams than Arecibo, mostly with Green Bank and Effelsberg (Nançay central measurements have not been considered, because of the small dimension of the beam, 3.′6 in the East-West direction). From Huchtmeier et al.'s (1983) catalogue of H I data and from Helou et al. (1984), we have found 23 such early spirals. The corrected Arecibo fluxes $F_{H_{cor}}$ and the total fluxes $F_{H_{tot}}$ derived from mapping or large beams measurements are in excellent agreement, except for NGC 4795, for which they differ by a factor of 16; however both Arecibo and Effelsberg H I profiles of this galaxy are of poor quality and therefore we remove it from the sample. Then we find:

$$\overline{\log \frac{F_{H_{corr}}}{F_{H_{tot}}}} = +0.04 \pm 0.03 \text{ (m.e.)}$$

Thus our corrections to Arecibo central measurements seem to be very good, with a low dispersion of only 30%.

### *5.3. The non-cluster comparison sample*

In order to study the H I contents of the early type spirals in the Virgo cluster, we first need to determine the average value of the gas content of the galaxies located out of it. We shall not use Arecibo observations for this purpose because they are not numerous enough and since the large beam corrections introduce some additional scatter in the H I contents. Instead, we shall use the H I measurements carried out by Bottinelli et al. (1980) and by Huchtmeier (1982) in early type spirals. Excluding the galaxies members of the Virgo cluster or of the Virgo extension and the confused galaxies, these two samples contain together 70 distinct galaxies, namely 21 S0/a (16 detections), 27 Sa (21 detections) and 22 Sab (20 detections). In order to deal with total H I fluxes for both samples, we have corrected for beam-filling the values corresponding to observations made only at the central position of the galaxy; the method of correction is the same as described hereabove for Arecibo measurements, using HPBW of 10′, 9′ and 3.′6 (in E-W) respectively for Green Bank 91 m, Effelsberg and Nançay radiotelescopes. We have incidentally remarked that the beam corrections given by Huchtmeier (1982) are underestimated, because they use corrected Holmberg diameters 50% too small on an average; this is not too disturbing however: the true correction factors remain only slightly larger than 1 (1.16 on an average) for his sample, whereas they are about 1.23 on an average for Nançay measurements. Note also that Bottinelli et al.s' fluxes are corrected for self-absorption contrary to Huchtmeier's ones; in order to insure homogeneity between the two samples, we have suppressed this correction for Bottinelli et al.'s fluxes. Anyway the correction is very small (1.03 on an average). Finally, for six detected galaxies appearing in both samples, the agreement be-

**Table 3.** Data for the non-cluster early spirals sample. *Col. 1*: Name of the galaxy: N for NGC, I for IC, A for anonymous. *Col. 2*: RC2 numerical morphological type. *Col. 3*: RC2 apparent major diameter in arcmin to surface brightness level 25 m/□″, corrected to face-on view and for galactic extinction. *Col. 4*: Radiotelescope used for the H I observations; E: Effelsberg 100 m and G: Green Bank 91 m (Huchtmeier, 1982); N: Nançay 200 × 35 m (Bottinelli et al., 1980). *Col. 5*: H I flux measured (or its upper limit) when pointing the radiotelescope at the center of the galaxy. *Col. 6*: Correction factor for beam-filling. *Col. 7*: H I mean surface density after correction for beam-filling. The underlined values correspond to galaxies mapped at Nançay, for which no correction for beam-filling is needed.

| Galaxy (1) | T (2) | $a_o$ (′) (3) | Tel. (4) | $F_{Hc}$ (Jy x kms$^{-1}$) (5) | $f_c$ (6) | $\sigma_H^t$ ($10^{-3}$g cm$^{-2}$) (7) |
|---|---|---|---|---|---|---|
| N 254 | 0 | 1.9 | N | 3.7 | 1.14 | 0.86 |
| N 357 | 0 | 2.6 | E | <4.9 | 1.11 | <0.61 |
| N 473 | 0 | 2.1 | G | 6.8 | 1.05 | 1.16 |
| N 660 | 1 | 8.0 | N | – | – | 2.48 |
| N 718 | 1 | 2.9 | G | <3.5 | 1.13 | <0.35 |
| N 1022 | 1 | 2.6 | G | <4.3 | 1.09 | <0.53 |
| N 1079 | 0 | 3.0 | E | 37.3 | 1.13 | 3.56 |
| N 1094 | 2 | 1.5 | N | 7.1 | 1.13 | 2.62 |
| N 1302 | 0 | 4.7 | E | 14.1 | 1.44 | 0.69 |
| N 1350 | 2 | 3.9 | N | – | – | 1.45 |
| N 1357 | 2 | 2.5 | G | <6.2 | 1.08 | <0.82 |
| N 1371 | 1 | 5.4 | E | 55.5 | 1.46 | 2.07 |
| N 1415 | 0 | 3.4 | E | 7.8 | 1.16 | 0.58 |
| N 1452 | 0 | 1.8 | E | 7.6 | 1.06 | 1.80 |
| N 2179 | 0 | 1.6 | N;E | 2.5; 1.9 | 1.08; 1.04 | 0.71 |
| N 2196 | 1 | 3.0 | N | – | – | 2.74 |
| N 2545 | 2 | 2.1 | N | 4.2 | 1.11 | 0.71 |
| N 2654 | 2 | 3.2 | N;G | 20.8;33.3 | 1.61;1.09 | 2.33 |
| N 2681 | 0 | 4.0 | G | <2.0 | 1.25 | <0.11 |
| N 2782 | 1 | 3.8 | E | 9.5 | 1.24 | 0.61 |
| N 2811 | 1 | 2 4 | N | <1.6 | 1.09 | <0.23 |
| N 2844 | 1 | 1.8 | G | 5.8 | 1.03 | 1.41 |
| N 2855 | 0 | 2.9 | E | <4.7 | 1.16 | <0.49 |
| N 2907 | 1 | 1.9 | E | <4.4 | 1.06 | <0.91 |
| N 2914 | 2 | 1.1 | N | 1.2 | 1.04 | 0.75 |
| N 2992 | 1 | 3.5 | E | 27.1 | 1.14 | 1.90 |
| N 3185 | 1 | 2.2 | G | 7.3 | 1.06 | 1.20 |
| N 3277 | 2 | 2.1 | G | 2.6 | 1.07 | 0.47 |
| N 3301 | 0 | 3.0 | G | <6.1 | 1.08 | <0.56 |
| N 3471 | 1 | 1.9 | N | 11.5 | 1.07 | 2.56 |
| N 3504 | 2 | 2.7 | N | 7.1 | 1.34 | 0.93 |
| N 3593 | 0 | 4.9 | E;G | 8.6;8.1 | 1.28;1.23 | 0.32 |
| N 3611 | 1 | 2.4 | N | 12.5 | 1.28 | 2.00 |
| N 3732 | 0 | 1.4 | G | 3.1 | 1.03 | 1.24 |
| N 3885 | 0 | 1.6 | E | 18.0 | 1.03 | 5.47 |
| N 3898 | 2 | 4.1 | G | 30.0 | 1.19 | 1.59 |
| N 4245 | 0 | 3.2 | G | <3.5 | 1.14 | <0.29 |
| N 4274 | 2 | 5.9 | E;G | 8.2; 9.2 | 1.39;1.32 | 0.25 |
| N 4314 | 1 | 4.9 | G | <4.1 | 1.36 | <0.18 |
| N 5014 | 1 | 1.4 | N | 5.3 | 1.12 | 2.06 |
| N 5037 | 1 | 2.1 | E | <6.2 | 1.05 | <1.10 |
| N 5101 | 0 | 5.9 | E | 34.7 | 1.65 | 1.22 |
| N 5377 | 1 | 4.3 | N;G | 14.6; 9.5 | 1.40;1.19 | 0.65 |
| N 5448 | 1 | 3.7 | N;G | 19.0;25.4 | 1.60;1.14 | 1.58 |
| N 5472 | 2 | 1.1 | N | 4.8 | 1.03 | 3.06 |
| N 5534 | 2 | 1.3 | G | 9.2 | 1.02 | 4.18 |
| N 5614 | 2 | 2.7 | N | 5.8 | 1.35 | 0.77 |
| N 5689 | 0 | 3.0 | G | 2.8 | 1.08 | 0.25 |
| N 5701 | 0 | 5.0 | N | – | – | 1.72 |
| N 5728 | 1 | 2.7 | N | 10.3 | 1.23 | 1.25 |
| N 5750 | 0 | 2.8 | E | 5.2 | 1.11 | 0.53 |
| N 5929 | 2 | 1.1 | E | 3.1 | 1.03 | 1.79 |
| N 6012 | 2 | 2.3 | N | 22.5 | 1.18 | 3.57 |
| N 6835 | 1 | 2.4 | E | 13.4 | 1.06 | 1.83 |
| N 6962 | 2 | 3.3 | N | – | – | 1.48 |
| N 7163 | 2 | 1.7 | N | 3.3 | 1.18 | 0.98 |
| N 7172 | 2 | 2.1 | N | <2.1 | 1.25 | <0.39 |
| N 7180 | 0 | 1.7 | N | 1.2 | 1.15 | 0.43 |
| N 7217 | 2 | 4.1 | N | 8.7 | 1.78 | 0.68 |
| N 7371 | 0 | 2.2 | G | 18.8 | 1.08 | 3.00 |
| N 7421 | 2 | 2.4 | N | 7.5 | 1.29 | 1.25 |
| N 7428 | 1 | 2.5 | N | 16.2 | 1.15 | 2.29 |
| N 7625 | 1 | 1.9 | E | 18.3 | 1.07 | 4.16 |
| N 7682 | 2 | 1.2 | N | 6.2 | 1.08 | 3.33 |
| N 7727 | 1 | 4.2 | N;E | 2.1;3.8 | 1.70;1.30 | 0.18 |
| N 7731 | 1 | 1.7 | N | 17.5 | 1.17 | 5.42 |
| N 7814 | 2 | 5.5 | N | – | – | 0.63 |
| I 1743 | 1 | 1.9 | N | 4.9 | 1.17 | 1.15 |
| I 5156 | 1 | 1.8 | N | 10.5 | 1.02 | 2.45 |
| A 145+12 | 1 | 1.0 | N | 6.7 | 1.05 | 5.44 |

tween the respective H I fluxes is far better after beam filling corrections than before, a result that is in favour of our correction procedure. The useful data relative to the early spirals of our sample are entered into Table 3.

Now we need to determine the average H I content of early spirals. As hereabove, we shall define the H I content by the parameter $\sigma_H$, which is well suited for this purpose, as being independent of any global parameter, in particular the linear diameter $A_o$. Indeed, for the detected early spirals of our sample, $\log A_o$ and $\log M_H$ exhibit a good linear correlation: $\log M_H = \alpha \log A_o + \beta$, with $\alpha$ not significantly different from 2 (least-squares fits lead to: $\alpha = 2.2 \pm 0.4$ and $\alpha = 1.8 \pm 0.3$ with correlation coefficients $r = 0.73$ and 0.67 for types 0 and 1 & 2 respectively). This proves that $\sigma_H \propto M_H/A_o^2$ does not depend significantly on $A_o$, as for later spirals.

Therefore we have to compute the average values of $\sigma_H$ for each type. For this purpose, we first determine the true distribution of $\sigma_H$ for each type in our sample. Here, contrary to the S0's, the proportion of detections is very high ($\sim 80\%$). Thus, for the derivation of the true $\sigma_H$ distributions from the corresponding distributions for detected galaxies, it is simpler to use Avni et al.'s (1980) method rather than ours since this method does not require the determination of the limits of detection for the measured objects. We obtain for types 0, 1 and 2 respectively: $\langle\sigma_H\rangle = 0.69 \pm 0.20$, $\langle\sigma_H\rangle = 1.58 \pm 0.30$, $\langle\sigma_H\rangle = 1.11 \pm 0.30$. Thus there is no significant difference in the H I contents between $T = 1$ and $T = 2$, whereas that of $T = 0$ seems slightly lower. Therefore we have merged types 1 and 2 obtaining: $\langle\sigma_H\rangle = 1.41 \pm 0.22$. We will not distinguish between $T = 1$ and $T = 2$ in the following, but $T = 0$ galaxies will be treated separately. Figures 9a and 9b show the corresponding $\sigma_H$ distributions: they appear symmetrical, so we can equal the mean $\overline{\log \sigma_H}$ and the median $\langle\log \sigma_H\rangle$, hence values given hereabove hold for the logarithmic average $\sigma_H$ values too. On the other hand, we can easily compute the dispersion $\sigma$ of the $\log \sigma_H$ around its mean value, obtaining: $\sigma = 0.45 \pm 0.06$ (m.e.) and $\sigma = 0.29 \pm 0.02$ (m.e.) for $T = 0$, and $T = 1$ and 2 respectively, values significantly higher than $\sigma \sim 0.2$ found for later spirals.

### 5.4. *The H I deficiency of the early spirals located in the Virgo cluster*

Table 4 gives the observational data necessary to study the H I content of the 42 early spirals of our Virgo cluster sample. The $\sigma_H$ values have been corrected for beam filling when necessary, and the deficiency parameter $DF$ is defined by $DF = \overline{\log \sigma_H} - \log \sigma_H$, where $\overline{\log \sigma_H}$ is the mean value for the morphological type as determined hereabove.

Notice that all the Virgo cluster early spirals except two have positive $DF$ values, indicating a clear H I deficiency. In fact the two galaxies with negative $DF$ have also an uncertain type in the RC2 and one of them. NGC 4383, could be confused. Thus it seems legitimate to exclude from our sample all the galaxies having an uncertain type in the RC2, namely NGC 4383, NGC 4452 and NGC 4470; NGC 4795 has also been excluded from the study because its H I profile is extremely doubtful.

Thus our final sample contains 23 galaxies in the Virgo cluster proper, among them 9 S0/a (2 detections), 8 Sa (4 detections) and 6 Sab (6 detections); and 15 objects in the Virgo cluster extension, 4 S0/a (3 detections), 7 Sa (6 detections) and 4 Sab (3 detections).

Our study will use the deficiency $DF$ instead of the mean H I surface $\sigma_H$, which allows to group several morphological types together. The true distributions and the mean values of $DF$ will be determined by Avni et al.'s (1980) statistical method, which is more appropriate than ours in the case of high detection rates, as shown by Chamaraux (1986).

Since the H I deficiency of late type spirals is limited to the Virgo cluster proper, we first examine the H I content of the early spirals in this region. The true distribution of their values is shown in Fig. 10; the average deficiency parameter is: $\overline{DF} =$

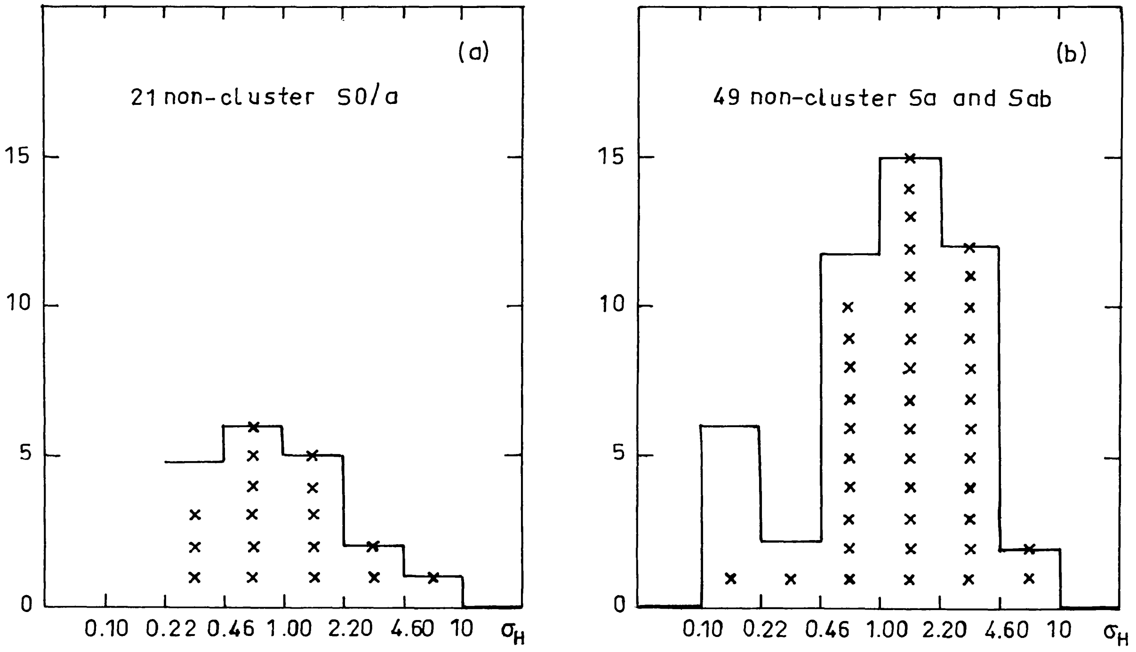

**Fig. 9a and b.** Distributions of the $\sigma_H$ (expressed in $10^{-3}\,\mathrm{g\,cm^{-2}}$) for 21 and 49 non-cluster S0/a, and Sa and Sab respectively

**Table 4.** Data for early spirals in the Virgo cluster and in its extension. *Col. 1*: Name of the galaxy: N for NGC. *Col. 2*: Cluster membership: Virgo for Virgo cluster; V. ext. for extension of the Virgo cluster; an asterisk stands for galaxies located at more than 10° from the cluster centre. *Col. 3*: RC2 numerical morphological type. *Col. 4*: RC2 apparent major diameter in arcmin to surface brightness level 25 m/□″ corrected to face-on view and for galactic extinction. *Col. 5*: H I total flux directly measured (except ref. 2) or corrected for beam filling from Arecibo measurement in the central position (ref. 2). *Col. 6*: Source of the H I fluxes: (1) Fisher & Tully (1981); (2) Giovanardi et al. (1983); (3) Giovanelli & Haynes (1983); (4) Helou et al. (1984); (5) Hewitt et al. (1983); (6) Huchtmeier (1982); (7) Huchtmeier & Bohnenstengel (1975); (8) Huchtmeier et al. (1976); (9) Krumm & Salpeter (1979b). *Col. 7*: H I mean surface density referred to the optical diameter, or its upper limit. *Col. 8*: H I deficiency factor, or its lower limit.

| Galaxy 1 | Cluster 2 | T 3 | $a_o$ (′) 4 | $F_H$ (Jy km$s^{-1}$) 5 | Ref 6 | $\sigma_H$ ($10^{-3}$g cm$^{-2}$) 7 | DF 8 |
|---|---|---|---|---|---|---|---|
| N 4045 | V.ext.* | 1 | 2.7 | 22.2 | 2 | 2.24 | -0.20 |
| N 4064 | V.ext. | 1 | 3.9 | 1.2 | 4 | 0.059 | 1.38 |
| N 4192 | Virgo | 2 | 7.8 | 83.9 | 1 | 1.03 | 0.14 |
| N 4260 | V.ext. | 1 | 2.3 | <2.1 | 4 | <0.282 | >0.70 |
| N 4293 | Virgo | 0 | 5.4 | <3.5 | 2 | <0.090 | >0.88 |
| N 4305 | Virgo | 1 | 2.0 | <1.1 | 2 | <0.21 | >0.83 |
| N 4312 | Virgo | 2 | 3.6 | 1.8 | 4 | 0.101 | 1.14 |
| N 4313 | Virgo | 2 | 3.0 | 1.9 | 4 | 0.154 | 0.96 |
| N 4351 | Virgo | 2 | 2.0 | 6.3 | 8 | 1.17 | 0.08 |
| N 4378 | V.ext. | 1 | 3.4 | 14.8 | 4,6 | 0.991 | 0.15 |
| N 4383 | Virgo | 1 | 2.0 | 44.2 | 4 | 8.21 | -0.77 |
| N 4405 | Virgo | 0 | 1.9 | 2.2 | 2 | 0.44 | 0.20 |
| N 4419 | Virgo | 1 | 2.8 | 2.8 | 9 | 0.26 | 0.73 |
| N 4421 | Virgo | 0 | 2.8 | <2.3 | 2 | <0.22 | >0.50 |
| N 4424 | Virgo | 1 | 3.4 | 3.1 | 4,6 | 0.200 | 0.85 |
| N 4438 | Virgo | 0 | 7.9 | 11.2 | 7 | 0.13 | 0.72 |
| N 4440 | Virgo | 1 | 2.0 | <1.19 | 4 | <0.221 | >0.80 |
| N 4450 | Virgo | 2 | 4.7 | 5.5 | 3,4 | 0.186 | 0.88 |
| N 4452 | Virgo | 1 | 1.8 | <1.3 | 4 | <0.290 | >0.69 |
| N 4454 | V.ext.* | 0 | 2.3 | 4.1 | 6 | 0.58 | 0.08 |
| N 4457 | V.ext.* | 0 | 3.0 | 7.4 | 2 | 0.61 | 0.05 |
| N 4469 | Virgo | 0 | 3.2 | <1.3 | 2 | <0.092 | >0.88 |
| N 4470 | Virgo | 1 | 1.5 | 8.4 | 4 | 2.84 | -0.30 |
| N 4483 | Virgo | 0 | 1.7 | <0.9 | 2 | <0.24 | >0.46 |
| N 4488 | Virgo | 0 | 3.2 | <1.7 | 2 | <0.12 | >0.76 |
| N 4491 | Virgo | 1 | 1.7 | <0.9 | 2 | <0.23 | >0.79 |
| N 4497 | Virgo | 0 | 2.0 | <1.0 | 2 | <0.18 | >0.58 |
| N 4531 | Virgo | 1 | 2.8 | 0.25 | 4 | 0.023 | 1.79 |
| N 4539 | Virgo | 1 | 3.1 | <2.3 | 4 | <0.178 | >0.90 |
| N 4569 | Virgo | 2 | 8.3 | 12.4 | 3 | 0.13 | 1.04 |
| N 4580 | V.ext. | 1 | 2.3 | 1.0 | 4 | 0.134 | 1.02 |
| N 4586 | V.ext. | 1 | 3.6 | 2.3 | 4 | 0.129 | 1.04 |
| N 4606 | Virgo | 1 | 2.5 | 0.54 | 2,4 | 0.063 | 1.35 |
| N 4643 | V.ext.* | 0 | 3.4 | 4.3 | 2 | 0.28 | 0.39 |
| N 4659 | Virgo | 0 | 1.8 | <1.3 | 2 | <0.29 | >0.38 |
| N 4698 | V.ext. | 2 | 3.9 | 41.6 | 4,6 | 2.03 | -0.16 |
| N 4772 | V.ext.* | 1 | 3.0 | 16.5 | 6 | 1.40 | 0.00 |
| N 4795 | V.ext. | 1 | 1.7 | 6.6 | 6 | 1.69 | -0.08 |
| N 4826 | V.ext.* | 2 | 8.7 | 51.2 | 5 | 0.50 | 0.45 |
| N 4845 | V.ext.* | 2 | 4.0 | <4.2 | 6 | <0.20 | >0.85 |
| N 4880 | V.ext. | 0 | 3.2 | 2.8 | 2 | <0.19 | >0.56 |
| N 4941 | V.ext.* | 2 | 3.4 | 7.9 | 6 | 0.51 | 0.44 |

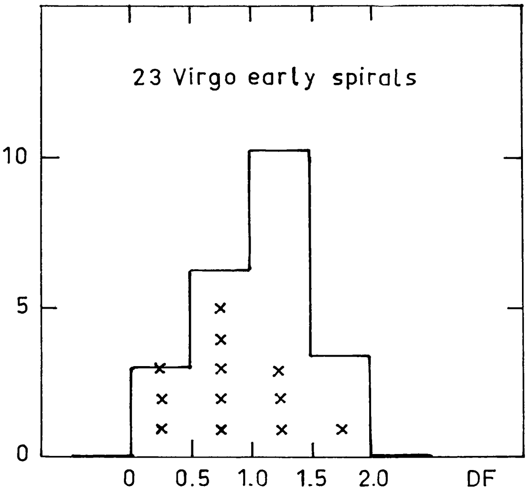

**Fig. 10.** True distribution of the deficiency parameter *DF* for 23 early spirals S0/a, Sa and Sab members of the Virgo cluster. The crosses correspond to the detected galaxies

1.05 ± 0.16, corresponding to a deficiency of more than a factor of 10. An H I deficiency higher than the average cluster one has already been found by Guiderdoni and Rocca-Volmerange (1985a) who have obtained: $\overline{DF} = 0.72 \pm 0.09$ for 18 spirals Sb and earlier. Their deficiency is smaller than ours by more than a factor of 2, mainly because their sample is very poor in types 0 and 1 (3 compared to 4 Sab's and 11 Sb's); therefore their *DF* value is mainly determined by the Sb's. Incidentally, note that the correction for the non-detections is essential in our computation of *DF*; indeed, we should obtain only $\overline{DF} = 0.77$ for $T = 0, 1, 2$ when taking the nominal upper limits of $\sigma_H$ as the actual $\sigma_H$ values for the non-detections.

The deficiency factor we find is much higher than the value 2.2 obtained for Virgo spirals Sb and later by Chamaraux et al. (1980). This difference is certainly not due to the different mean distances to the centre of the cluster, which are 3°0 and 3°2 for early spirals of our sample and for Chamaraux et al.'s sample respectively. Instead we think that the high deficiency is related to the fact that the neutral gas in the early spirals is distributed mainly in the outer parts and is thus very sensitive to stripping.

If this hypothesis is correct, the Virgo cluster S0' are expected to present still higher deficiencies than early spirals. On the other hand, it is quite remarkable that with such a high gas deficiency, an average Virgo early spiral contains less H I than a non-cluster S0! Consequently, in the absence of a quick and efficient gas replenishment, these spirals are likely candidates to form future S0's. We will come back to this important point in the next section.

We end this section looking for any correlation between the H I deficiency and other parameters:

### 5.4.1. Variation of DF with the morphological type

Since the H I deficiency in the Virgo cluster increases considerably from late to early spirals, it is interesting to see whether it also increases from type 2 to 0. The simple examination of the detection rates suggests this is the case; more quantitatively, we find: $\langle DF \rangle > 1.0$ for the 9 S0/a's, $\overline{DF} = 1.34 \pm 0.13$ for the 8 Sa's and $\overline{DF} = 0.72 \pm 0.17$ for the 6 Sab's.

Although the samples are small, it seems to exist a significant increase of *DF* from the types 2 to 0; the *DF* value for $T = 0$ is only an upper limit, due to the lack of detections, but $\frac{2}{3}$ of the S0/a's are found to have $DF > 1.0$, indicating an average *DF* significantly higher than this limit.

We can now go further on, and look for a possible variation of *DF* in Virgo later spirals. Using the Virgo H I data gathered by Guiderdoni and Rocca-Volmerange (1985a) (the galaxies NGC 4567, NGC 4294 and NGC 4299 have been removed because of confusion), completed by a few objects in Helou et al.

(1984), and the $\sigma_H$ comparison values for non-cluster galaxies given by Bottinelli et al. (1982), we obtain:

$\langle DF \rangle = 0.51 \pm 0.09$ for 13 Sb's ($T = 3$)

$\langle DF \rangle = 0.42 \pm 0.12$ for 7 Sbc's ($T = 4$)

No clear variation appears among later types; moreover the samples are small for each of them; so we can group them together, and we find: $\langle DF \rangle = 0.20 \pm 0.06$ for 16 types Sc to Sm ($T \geq 5$).

Hence a continuous decreasing of the H I deficiencies in the Virgo cluster proper is apparent from types 0 to 5, in excellent agreement with what is expected on the basis of the H I spatial distributions if stripping by the intracluster medium is the cause of the cluster deficiencies.

### 5.4.2. Variation of DF with the distance to the cluster centre

We looked for such a variation considering separately each type 0, 1 and 2 because of the previous result. There is no evidence of such a gradient. Instead, we have found that, contrary to what occurs with later spirals, the deficiency of the early spirals extends at least to 10° from the cluster centre. We obtain: $\overline{DF} = 0.85 \pm 0.21$ and $\overline{DF} = 0.33 \pm 0.28$ for the 7 Virgo extension early spirals located between 6° and 10° and for the 8 ones located at more than 10° from the centre, respectively. This result is not related to the proportion of various types, which is not very different in the two subsamples. It can be compared to Huchtmeier's (1982) result, who has found that the Sa's located at less than 7 Mpc from the Virgo centre (and the majority of the ones he has considered are out of the Virgo cluster proper) have twice less H I than the other ones of his sample.

Finally, the average $DF$ within 10° from the cluster centre is: $\overline{DF} = 0.99 \pm 0.13$, not significantly different from the value obtained for the Virgo cluster proper.

### 5.4.3. The East-West effect

The early spirals located in the Western half of the Virgo cluster are marginally less deficient than those located in the Eastern half, with $\langle DF \rangle = 1.0 \pm 0.16$ and $\overline{DF} = 1.52 \pm 0.19$ respectively. In order to remove the type effect, we have limited the comparison to types 0 and 1, which are almost in equal number in the two halves, contrary to Sab types. This curious East-West effect has already been noticed by Chamaraux et al. (1980) for later type spirals, and is visible on Fig. 2 in Haynes (1985).

At last, as a final check of the validity of our beam corrections in the Virgo cluster proper, we have compared the values of $\overline{DF}$ found for 6 Virgo Sa galaxies mapped or observed with a large beam and for 7 Virgo Sa's observed at their central position and corrected for beam filling as explained hereabove. The respective values are 1.40 and 1.34 (note that these galaxies are well distributed between the Eastern and the Western halves). Thus our beam correction introduces no bias in the above results, contrary to what could have been suspected on the basis of possible reduced H I diameters for Virgo early spirals.

## 6. The origin of the S0's

The most fascinating problem about the S0's is certainly the question of their origin. Are they primordial, having been formed initially as S0's, or do they originate from ancient spirals having lost their gas after a close encounter or a complete gas stripping by the intracluster medium for instance, or still can they have one or the other of these two origins, depending on their environment? (cf. Sandage and Visvanathan, 1978; Dressler, 1980; Larson et al., 1980; Balkowski, 1983; van Woerden et al., 1983 for discussions). And what contribution can our results bring to this problem?

First, we note that the elements of information we can give are of different nature for non-cluster S0's and for Virgo cluster ones. Indeed, in the case of the former, the H I global properties are accurately known for 60% of them, i.e. the majority; in the case of the Virgo cluster S0's, on the contrary, the H I contents are determined for 7% of the population, the other ones being upper limits; but we have also brought to light another important piece of information, namely that the Virgo early type spirals have an H I content similar to the one of the non-cluster S0's.

Hence we shall discuss separately the non-cluster S0's and the Virgo cluster ones.

### 6.1. *The non-cluster S0's*

One striking feature clearly emerges from our study: on the point of view of the H I properties, the non-cluster S0's seem to normally extend the sequence of spirals beyond the earliest types. This can be seen in several ways:

(i) As seen in Sect. 4, the S0's follow the same relationship $M_H \propto A_o^2$ between their diameters and their H I masses as the spirals do: this shows that the global relation between gas and stars is analogous in S0's and in spirals.

(ii) The H I contents steadily increase from types −3 (S0) to 10 (Irr), without any peculiar discontinuity between S0's and spirals.

(iii) As shown by van Woerden et al. (1983), the H I spatial distribution in S0's extends more or less than the one found in spirals, towards distributions always less centrally concentrated, when going from late spirals to S0's.

That continuity of the H I properties between spirals and lenticulars seems to argue against an "accidental" origin of non-cluster S0's from spirals. Indeed, if a spiral has led to a S0 after gas ablation and if the gas now present in the S0 has been subsequently accreted from the external medium or in any other way, one would expect a very high dispersion of the H I contents of the S0's, which is not observed, at least for those objects having $\sigma_H \geq 0.10$. Thus our results rather point towards a primordial origin for the non-cluster S0's; the continuity between the initial conditions that have led to S0's and spirals is indeed reflected in the present observed continuity between the two groups. But we emphasize again the character essentially limited of our conclusions.

Recently, Icke (1985) has proposed an interesting scenario to form S0's from distant encounters between spiral galaxies, the effect of which would remove gas from them by tidal effects and sudden stellar formation. From his model, he can find again the correlation obtained by Dressler (1980) between the galaxian density and the percentage of S0's, which makes his scenario credible. In such a model, it seems that one would also expect some correlation between the H I content of a S0 and the galaxian density, since encounters are more frequent in regions of high galaxian density. The corresponding plot for non-cluster S0's is shown in Fig. 11; no such correlation is visible; however, due to the high proportion of upper limits, a correlation would not be necessarily seen, even though it was actually present.

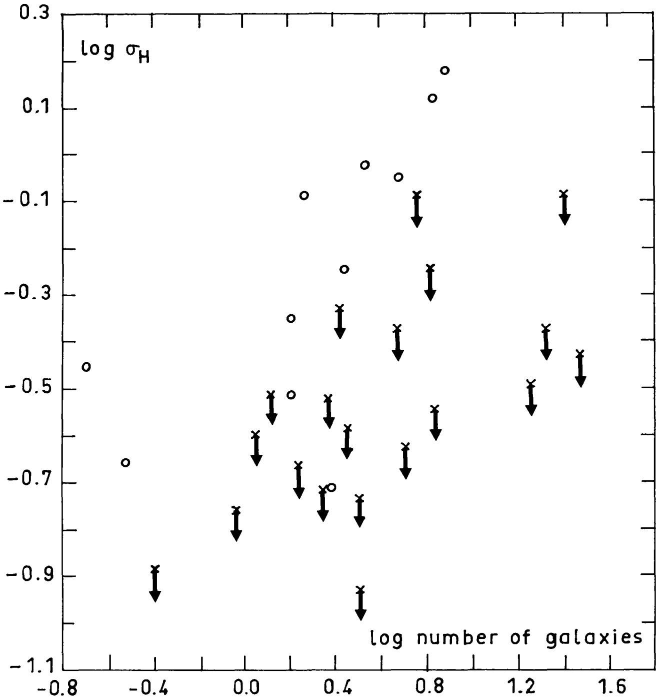

**Fig. 11.** Plot of $\log \sigma_H$ (expressed in $10^{-3}$ g cm$^{-2}$) versus the local galaxian density for the detected (circles) and the undetected (arrows) non-cluster S0's redshifts of which are between 1000 and 6000 km s$^{-1}$. The galaxian density is defined as the number of galaxies reported in the Zwicky CGCG (Zwicky et al., 1961–1968) that lie within a 1 Mpc radius circle centered on the sample S0, and brighter than $M = -18.4$ if at the same distance as the S0; a statistical correction has been applied for background and foreground contaminations

### *6.2. The Virgo cluster S0's*

Our analysis of the H I content of the Virgo cluster S0's mainly shows that these galaxies are probably very deficient in gas compared to the non-cluster ones. But we have also found that early-type spirals in the Virgo cluster are so much gas-deficient that their present H I content is not higher than the one of the non-cluster S0's, making them *obvious candidates for future lenticular galaxies.* We want now to explore that possibility, which means, according to us, that at least some proportion of the S0's in the Virgo cluster (and in other clusters as well) can originate from spirals stripped by the intracluster medium.

First note that the study of the infrared excesses provides another independent piece of evidence in favour of the similarity of the H I contents in the Virgo early-spirals and in the S0's. Indeed, De Jong (1985) has compared from the IRAS data the infrared excesses $\log L_{IR}/L_B$ in the galaxies of the same morphological type located within and out of the Virgo cluster. He has found no difference for the S0's and the late spirals respectively. In turn, he has shown that the Sa/bc galaxies in the Virgo cluster have significantly smaller infrared excesses than their field counterparts, their excesses being similar to the ones of the S0's. He interprets these results by a reduction of the star formation rate in the Virgo early-spirals by about a factor of two compared to what occurs in the field ones; in fact, his data also suggest similar star formation rates in the S0's and in the Virgo Sa/bc. These conclusions are in total agreement with our results concerning the very high H I deficiencies of the Virgo early spirals (compared to the late ones after Sc), and the similarity of the H I contents of these objects and of the S0's. In fact, this remarkable agreement also provides an excellent indirect evidence of the correctness of our method of analysis of the H I contents of the S0's and of the Virgo early spirals.

An interesting point which clearly emerges from Fig. 10 is that all the Virgo early spirals are H I-deficient, and that only 13% are possibly deficient by less than a factor of 3. In fact, the *DF* distributions for Virgo early-spirals and for the non-cluster ones have similar dispersions (0.48 and 0.37 respectively); hence there is a real possibility that all the Virgo early-spirals have more or less the same high deficiency of a factor of 10, the ones with $DF < 0.5$ simply coming from spirals having initial H I contents higher than the average for their type. We must emphasize here that the parameter *DF* has only a statistical meaning; for a given galaxy, *DF* does not represent its actual H I deficiency, but the deficiency it would have if its initial H I content was exactly the average one for its type. Whatever it may be, all this shows that a Virgo early spiral cannot recover its normal H I content after stripping. In the case of a stripping caused by interaction with the intracluster medium in the central regions of the cluster, this result can also be found by the following simple estimate. Faber and Gallagher (1976) give an ejection rate from evolved stars of $0.015\,M_\odot$ yrs$^{-1}$. $(10^9\,L_\odot)^{-1}$ for early-type galaxies. The average time spent by a galaxy between two passages in the central regions of the cluster is $\sim 2.5\,10^9$ years (assuming radial trajectories and a 2 × 6° crossing length); thus the $M_H/L$ maximum acquired by star mass loss during this time is $0.03\,M_\odot/L_\odot$ (assuming that all the hydrogen ejected is in H I form), leading to $0.044\,M_\odot/L_\odot$ if the H I deficiency by stripping is of a factor of 10; this is 3.5 times less than the normal H I content of an early spiral. And here, we have not considered the galactic winds which could remove gas from the early spirals as they probably do from S0's.

Thus the similarity of the H I contents of S0's and Virgo early spirals galaxies and the absence of any sufficient gas filling process of the latter makes the transformation of early spirals into S0's a likely event, occurring a few galactic rotations ($\sim 10^9$ years) after the stripping. Note that the similarity of the bulge/disk ratios in S0's and Sa's (Simien and de Vaucouleurs, 1983) does permit such a transformation.

Now we can try to determine whether the majority of the Virgo S0's can have originated in this way. We shall only make some very simple semi-quantitative estimates concerning a possible scenario for that process. A detailed study would require models of galactic evolution which are out of the scope of the present paper. Guiderdoni and Rocca-Volmerange (1985b) have in fact already obtained several results from such models; in particular, they have shown that the Virgo spirals in their present morphological types have experienced at most two strippings. If such strippings are caused by the ram-pressure of the intracluster medium and hence correspond to plunges of the galaxies in the centre of the Virgo cluster, that means that the spirals have existed in their present morphological type for 2 to $3\,10^9$ years at most. This short time-scale is in good agreement with Tully and Shaya's (1984) findings. Indeed these authors, analyzing the velocities and the distances of the spirals located in the Virgo Southern extension, have convincingly shown that this cloud of galaxies has been continuously falling into the Virgo cluster since the last $4\,10^9$ years. According to them, the Virgo extension has provided to the

Virgo cluster most of the disk-galaxies it contains presently, its ellipticals having probably been present in it at the origin.

If this model is correct, then the present proportion of disk-galaxies of various types in the Virgo extension is a good indication of the one which should be presently found in the Virgo cluster in the absence of any stripping of the spirals, and therefore the comparison with the actual composition of the cluster shows the effect of stripping after $4\,10^9$ years. From de Vaucouleurs (1961), we have determined the percentages of disk-galaxies of various morphological types in Virgo I and Virgo X (which is a part of Virgo II). De Vaucouleurs' (1961) catalogue is fairly complete up to $m = 13.5$; there are 113 and 35 disk-galaxies in Virgo I and Virgo X respectively. In order to deal with significant numbers, we have grouped neighbouring types together; the results are entered into Table 5. As it can be seen, the percentages differ uniquely for S0's and for late-type spirals in Virgo I and in Virgo X (in agreement with Gisler's (1980) results for other clusters), as if all the late-type spirals injected in Virgo I had been transformed into S0's. But such a direct transformation is ruled out because of different bulge-to-disk ratios b/d and because present Virgo late-spirals are far from being deficient enough to lead to S0's. In turn, it is certainly not excluded that a less radical transformation can occur, in which Sd's, Sbc's and Sa's give Sbc's, Sa's and S0's respectively. Indeed, first such a stripping is compatible with corresponding changes in b/d ratios (Guiderdoni and Rocca-Volmerange, 1985b); second it is compatible with H I deficiencies presently observed, since Virgo spirals of a given morphological type T have the H I contents of the normal ones having a type T-2, as already noted by Kennicutt (1983) for Sb's and Sc's and shown in Table 5 for any type. Hence, after some time, these Virgo spirals will acquire the morphology corresponding to T-2 and will become quickly deficient again for their new morphological type. So one can think that the 27% late-type galaxies lacking in Virgo I have turned into Sb-Sbc's, and that in the same time Sb-Sbc's have been transformed into Sa's, and Sa's into S0's, corresponding to galaxies entered into Virgo before $\sim 1$–$2\,10^9$ years, the respective percentages of S0/a-Sab's and of Sb-Sbc's remaining constant in the transformation. In such a picture, the 25% present Virgo late-spirals would be recent arrivals, and several of them are already in the process of conversion into Sb-Sbc's. Of course, in the next $10^9$ years, all the present Sa's will have given S0's, the proportion of which will have almost doubled.

**Table 5.** Percentages of the different morphological types in the Virgo cluster and the Virgo X cloud with the corresponding mean H I surface density. *Col. 1*: Morphological types. *Col 2*: Percentage of disk-galaxies of the morphological type with $m_B < 13.5$ in the Virgo X cloud. *Col. 3*: Same quantity as in column 2 for the Virgo cluster galaxies brighter than $m_B = 13.5$. *Col. 4*: Average $\sigma_H$ in $10^{-3}\,\mathrm{g\,cm^{-2}}$ for field galaxies (from the present paper, and from Bottinelli et al. (1982) for spirals later than Sb). *Col. 5*: Average $\sigma_H$ in $10^{-3}\,\mathrm{g\,cm^{-2}}$ for the Virgo cluster galaxies (from the present paper, and Guiderdoni & Rocca-Volmerange, 1985a, for types later than Sb).

| Type<br>1 | % V.X<br>2 | % V<br>3 | $\bar{\sigma}_H$ field<br>4 | $\bar{\sigma}_H$ V<br>5 |
|---|---|---|---|---|
| S0 | 6 | 32 | 0.13 | <0.10 |
| S0/a-Sab | 26 | 27 | 1.0 | 0.09 |
| Sb/Sbc | 17 | 17 | 2.2 | 0.8 |
| Sc-Irr | 52 | 25 | 2.9 | 1.9 |

Thus, within the frame of Tully and Shaya's (1984) model, the data are compatible with the hypothesis that most of the Virgo S0's have been formed from spirals. These considerations also show that the complete stripping of late spirals is not extremely fast, since it needs a number of passages of the galaxies through the central regions of the cluster; that cascade process could explain in the same time the excess of S0's and the lack of late-spirals in other clusters (compared to the field). If stripping by the intracluster medium is the actual cause of the gas deficiencies, the lack of late-spirals would be particularly obvious in the X-ray clusters.

## 7. Conclusion

The use of a new statistical method described in Sect. 2 has allowed to study the true distribution of the H I contents of the S0 galaxies, despite their low detection rate in the H I line. The basic sample used comprises the 122 S0's observed at Arecibo with a high sensitivity (only 31 detections) and their H I content is defined by the H I mean surface density $\sigma_H$ which appears as the best parameter for that purpose ($\sigma_H$ is expressed in $10^{-3}\,\mathrm{g\,cm^{-2}}$ in the whole paper).

The main results are the following:

(i) The S0's of our sample members of the Virgo cluster have H I contents much lower than the ones located outside of any cluster.

(ii) Among the 62 S0 galaxies not belonging to any cluster, 60% (±14%) have $\sigma_H \geq 0.10$ (or 44% ± 13% after corrections for the probable presence of about 20% spirals in our sample). The function of distribution of their H I contents increases at low $\sigma_H$ values; if the distribution of $\log \sigma_H$ for the whole non-cluster S0 sample is symmetrical, then the logarithmic mean value of $\sigma_H$ is: $\bar{\sigma}_H = 0.13$, (or $\sim 0.08$ after corrections for spirals), that is about 5 times less than for the earliest spirals S0/a.

(iii) The H I content of the non-cluster S0's is found to increase by more than a factor of 3 along the sequence of de Vaucouleurs lenticular types $-3$ to $-1$.

(iv) Among 42 lenticular galaxies members of the Virgo cluster, only 7% have $\sigma_H \geq 0.10$, which indicates a clear H I deficiency which cannot be estimated quantitatively however, because the upper limits of detection are still not low enough.

(v) The H I contents of 23 S0/a, Sa and Sab galaxies members of the Virgo cluster have also been analyzed by a similar statistical method. They are found H I deficient by a factor of 11, i.e. 4 times more than the later spirals; with such a high deficiency, they do not contain more H I than the non-cluster S0's. On the other hand, the deficiency of the Virgo cluster spirals decreases continuously along the type sequence from S0/a to Sc. These results are consistent with stripping by the intracluster medium as the cause of the deficiencies, and from this result one can infer still higher deficiencies for cluster S0's.

(vi) The problem of the origin of the S0's is discussed, in relation with the previous results.

### *7.1. The non-cluster S0's*

The general continuity of the properties between early spirals and S0's, the relatively low dispersion of the H I contents of the S0's and the lack of any correlation between these and the galaxian density argue in favour of a primordial origin for the non-cluster S0's rather than an accidental one from ancient spirals. These conclusions could be notably specified by two observational improvements:

– deep plates of a larger number of S0's, in order to remove the early spirals from the sample studied;

– H I observations of the S0's with a higher sensitivity: for instance, a gain of a factor 2 in sensitivity would probably allow to know the accurate distribution of the H I contents for 70–80% of the S0's of our sample, instead of 50–60% presently.

### 7.2. *The Virgo cluster S0's*

Having the same H I contents as the non-cluster S0's, the Virgo cluster early spirals are excellent candidates for future S0's, and it seems inescapable that at least a few Virgo S0's have been formed from them. In the frame of Tully and Shaya's (1984) model, in which the galaxies of the Virgo Southern extension have continuously fallen into the Virgo cluster and have provided most of the spirals presently found in it, a transformation of spirals into S0's is in fact needed to explain the lack of late-spirals in the cluster compared to what is found in the Virgo extension, the percentage of the other spirals remaining the same in each of them and the proportion of S0's being of course higher in the cluster. The direct transformation of late-spirals into S0's being ruled out, we suggest a process in which each spiral of type T gives one of type T-2 after stripping. This is in good agreement with the data on deficiencies and the effect of stripping on the b/d ratios. In this scheme, most of the Virgo cluster S0's could have originated from the early-spirals having fallen into the cluster before 1 or 2 $10^9$ years ago.

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