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H I IN EARLY-TYPE GALAXIES. I. OBSERVATIONS

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ABSTRACT

New 21-cm observations of 25 E and S0 galaxies provide a basis for an observational study of relationships between H I content and other properties of early-type systems. Only two galaxies in the sample, NGC 2685 (S0p) and the normal S0 NGC 5102, are detected. Previously reported detections of NGC 1332, NGC 3115, NGC 4274, and NGC 4526 are not confirmed. A very low limit of $M_{\rm H\,I}/L_{\rm pg} < 0.007$ is also measured for the Sombrero Galaxy, NGC 4594. By assuming that the undetected E's and S0's are representative of homogeneous populations, limits for mean E and S0 galaxies of $\langle M_{\rm H\,I}/L_{\rm pg}\rangle < 0.009$ and <0.015, respectively, are found.

All available H I observations of early-type galaxies are used to generate a list (containing four normal S0's and 12 peculiar galaxies) of high-probability detections. From these data and our new measurements, we conclude:

1. Elliptical galaxies contain at most 0.1 percent H I by mass. This is consistent with other observed features such as lack of internal reddening, dust lanes, and H II regions, all of which indicate that little interstellar matter is present.
2. Some structurally normal S0 galaxies exist with $M_{\rm H\,I}/L_{\rm pg} \gtrsim 0.05$, while other, apparently similar, systems have upper limits $M_{\rm H\,I}/L_{\rm pg} < 0.03$. In the available small sample of normal S0's, H I content does not correlate with the presence of dust lanes, optical emission, or even blue colors. The most hydrogen-rich S0's have relative H I masses as large as those found for some normal Sb spirals.
3. In terms of H I content, the S0 class appears to be a true transition between the H I properties of spirals and ellipticals. The present data do not support the conclusions of earlier surveys which found the H I content of normal S0's to be anomalously large.
4. In some galaxies an extensive interstellar medium is obviously present, but has different properties from those usually found in later type spirals. For example, dust is present in NGC 4594 but no H I is detected, while NGC 5102 contains H I but no detectable dust.
5. Among ᵗhe morphologically peculiar early-type galaxies, those which exhibit violent activity are rich in H I. In these galaxies, other signs of interstellar matter such as dust of young stars are often present.

Subject headings: galaxies — interstellar matter — nebulae — 21-cm radiation

I. INTRODUCTION

Recently there has been increased interest in the properties of the interstellar medium in early-type (E, S0, Irr II) galaxies. In particular, several surveys have been made for 21-cm emission with the intent of extending the well-known correlation between H I content and morphological type to earlier classes (Roberts 1969, 1972; Balkowski *et al.* 1972 and references therein; Lewis and Davies 1973). However, these surveys have produced some rather unexpected results.

On the basis of colors (de Vaucouleurs and de Vaucouleurs 1972) and a few more-detailed photometric studies (Lasker 1970; Spinrad 1972), the S0 galaxies are thought to have stellar populations quite similar to those found in ellipticals. But from the presently available small sample of observed galaxies, S0 systems sometimes contain H I, while ellipticals do not. Elliptical galaxies have been studied at 21 cm by Gallagher (1972), Bottinelli *et al.* (1973), Guibert (1973), and Knapp and Kerr (1974*a*). These observations have set upper limits for the H I content at 0.1 percent or less of the total mass. No elliptical has ever been detected at 21 cm. In contrast, certain morphologically normal S0 galaxies such as NGC 1291 or NGC 1326 reportedly have fractional H I masses comparable to those usually found for spirals of type Sb or later (Lewis 1970; Balkowski *et al.* 1972).

This difference between the H I masses in ellipticals and S0's would seem to indicate that galaxies may exist in which the properties of the interstellar medium are not strongly correlated with the present stellar population. As a result, the classical model of an S0 galaxy as a system without sufficient gas to form new stars (Sandage *et al.* 1970) becomes questionable. The observations of early-type systems may also have a bearing on understanding the existence of a morphological sequence among all normal galaxies. An understanding of the mechanisms governing gas content in early-type galaxies may simultaneously clarify the nature of these systems themselves as well as the relationship of early-type galaxies to the remainder of the Hubble sequence. To this end, more sensitive observations of E and S0 galaxies are clearly important.

A second and related problem concerns the lack of interstellar matter in elliptical galaxies. Since ellipticals include the most massive galaxies (e.g., NGC 4472), it might be expected that the effects of mass loss during stellar evolution would be pronounced, but both H I upper limits and the observed fossil stellar populations are consistent with an interstellar medium of low total mass (Tinsley 1972; Gallagher 1972; Knapp and Kerr 1974*a*). If stars are losing mass, then gas must either be hidden in some unobservable form or removed from the galaxy (Mathews and Baker 1971; Faber and Gallagher 1975, hereafter Paper II). We shall see that whatever mechanisms are invoked to limit the amount of gas in an elliptical galaxy such as a normal E5 must *not* remove gas from at least a few S0 systems.

In this paper we present an observational discussion of problems related to the H I content of early-type galaxies. We have made new measurements of several galaxies which are presented in § II of the paper. As instrumental effects can mimic the appearance of a faint signal, considerable attention has been paid to the criteria used to define a detection. A comparison is made between the available sets of 21-cm observations in § III, and a list of galaxies with high-quality detections is produced. We then give, in § IV, an overview of some implications of the measurements of H I in early-type galaxies, and in § V present a tentative set of conclusions. These data are further discussed in Paper II in terms of the relations between the mass of the interstellar medium, the stellar content, and dynamical properties of galaxies.

II. NEW 21-CM OBSERVATIONS

Ten morphologically normal elliptical galaxies, mainly with low ellipticities, were included in the H I surveys by Gallagher (1972) and Bottinelli *et al.* (1973). The lack of detections for these galaxies and the very low upper limit for the mass of H I in NGC 4472 set by Knapp and Kerr (1974*a*) lead to the tentative conclusion that most spheroidal E galaxies contain at most very low masses of H I. In selecting galaxies for our program, we therefore preferred E5–7 systems as a check against the possibility that H I might be more common in flattened galaxies. The normal S0 galaxy candidates were chosen to include both systems such as NGC 3115 and NGC 5102, for which detections had been previously reported at 21 cm (Balkowski *et al.* 1972; Lewis 1970), as well as a selection of heretofore unobserved galaxies. A few peculiar S0's and the unusual Sa system NGC 4594 were also observed. We also attempted to sample both field galaxies and galaxies in clusters or de Vaucouleurs (1975) groups, as it is possible that the cluster environment might inhibit the ability of a galaxy to retain H I (Lewis and Davies 1973).

It was necessary to choose candidate galaxies that did not have nearby neighbors which might have caused confusion. Galaxies which had neighbors within a radius of 10′ and redshifts within 300 km s^{-1} of the candidates, or had a neighbor with an unknown redshift, were generally excluded. This decision was made on the basis of a visual examination of *Palomar Sky Survey* prints and thus was somewhat flexible; for example, galaxies near faint dwarf elliptical systems were not excluded. In two cases we were able to observe two galaxies simultaneously at the same telescope position since the separations of the NGC 4473/4477 (13′) and NGC 4762/4754 (10′) pairs and the angular diameters of the galaxies are considerably less than the beam size. Observations of the pairs were made by centering the beam between the two galaxies (although the H I mass for NGC 4477 has been corrected for some observations which were made centered on NGC 4473). We also preferentially selected galaxies with revised Hubble types on a list supplied by Sandage (1974). We thereby hoped to avoid inhomogeneities in our sample due to differing classification systems as much as possible. A uniform system of classification also facilitates the identification of structurally peculiar galaxies.

The observations were made in 1974 February using the 140-foot (43 m) radio telescope at the National Radio Astronomy Observatory.[1] The aperture efficiency, i.e. the combined effects of electrical losses, spillover, and sidelobe dilution, is a factor of 0.57[2] for the galaxies observed (all of which were unresolved to the 20′ beam). A dual-channel receiver which was tunable between 1380 and 1430 MHz was used in conjunction with a pair of 192-channel autocorrelators in order to provide two simultaneous and independent 10 MHz total bandwidth (2000 km s^{-1}) spectra centered at identical velocities. Each channel then corresponds to a velocity interval of about 11 km s^{-1}. The system temperature in each channel was $\sim$45 K, and the rms noise in each spectral channel was typically 0.003 K (after smoothing over three channels) for the integration times obtained for the weak or undetected galaxies. The "total power" method was employed throughout; i.e., alternate observations of the program galaxies and nearby galaxy-free sky were made in a 10-minute cycle using the same receiver settings.

The ultimate limitation encountered in the detection of wide ($\sim$1 MHz) lines expected from galaxies originates from instrumental fluctuations which cause curvature in the spectral baselines. These fluctuations arise from short-term receiver instabilities and are

[1] Operated by Associated Universities, Inc., under contract with the National Science Foundation.

[2] A more reasonable efficiency for this receiver system is about 0.5 (M. S. Roberts, private communication). Thus all H I masses and upper limits in this paper should be increased by 15%.

similar in appearance to a weak, broad line. Systematic variations across the bandpass with amplitudes of 0.1 to 0.5 K were sometimes observed; fortunately, it was found that the shapes and alignments of these features tended, within limits, to be random and different in the two channels. Consequently, the final spectra were made by combining a large number (typically 20) of the best observations. Often the effects of baseline curvature were most severe near the ends of the bandpass, and thus the final data processing was often carried out over only the central 8 MHz. Similarly, for galaxies with small redshifts, the region containing galactic H I was also deleted before final reductions were undertaken.

The data were smoothed with a 3-channel (33 km s^{-1}) rectangular function, and a linear baseline was fitted by removing a slope and constant offset. For spectra in which a signal was present, the fitting region excluded the velocity interval containing the line profile. The removal of this baseline does not introduce spurious features, nor does it affect the results obtained for the detected lines. After this processing, the spectra often still contain large-scale structure due to the residual effects of baseline curvature, even when no signal is obviously present. In computing an upper limit for a detectable signal, the effects of this curvature must be explicitly allowed for.

One approach to producing a mean upper limit to the antenna temperature T_A over some representative velocity interval ΔV is to difference the mean T_A in an interval centered on the galaxy's optical velocity V_0, with the T_A calculated from comparison velocity intervals having the same ΔV centered at velocities $V_0 + \Delta V$ and $V_0 - \Delta V$ (e.g., Gallagher 1972). Unfortunately, for realistic values of $\Delta V \sim 300$ km s^{-1}, the upper limit to T_A found by this technique contains information from only part of the spectrum, and is therefore sensitive to the scale of the baseline curvature. An alternative approach is to find an upper limit to T_A from the rms deviation of all of the statistically independent 33 km s^{-1} points across the entire spectrum. A signal was considered real only if it exceeded 3 times this deviation; thus the upper limit to T_A is formally a 3 σ limit (although the deviations from the mean were sometimes a noticeably nonnormal distribution). The upper limits found in this way are considerably larger than would have been theoretically predicted from the system temperature and integration times. In searching for weak, broad signals, receiver stability, not system temperature, is therefore the ultimate limiting factor.

The results of the observations are listed in Tables 1 and 2 in terms of the distance-independent mass factor F, which is defined by

$$F = \frac{M_{\mathrm{H\,I}}}{D^2} 10^6 \, M_\odot \, \mathrm{Mpc}^{-2} \, . \qquad (1)$$

This form of the measured line flux at 21 cm allows a convenient comparison to be made between the H I masses measured by different observers. For a source much smaller than the beam size, an approximate integration of T_A over the beam response and velocity can be used to find F from measured quantities (e.g., Gallagher 1972)

$$F = 3.08 \frac{\lambda^2}{\eta A} \int_0^\infty T_A(\nu) d\nu$$
$$\approx 0.793 \langle T_A \rangle \Delta V \, 10^6 \, M_\odot \, \mathrm{Mpc}^{-2} \, . \qquad (2)$$

Here λ is the wavelength, η the aperture efficiency of 0.57, A the dish area, $\langle T_A \rangle$ the mean antenna temperature, and ΔV the velocity interval over which the H I is spread. In using this formula we are of course assuming that the H I spin temperature is considerably larger than 3 K, and that the optical depth is small. For the galaxies in Table 1 which are not detected, $\langle T_A \rangle$ is the 3 σ upper limit from the 33 km s^{-1} intervals, and ΔV was taken to be 300 km s^{-1} for a typical early-type galaxy (e.g., Morton and Chevalier 1972). Galaxies for which signals were definitely detected are given in Table 2; in this case ΔV and T_A could be determined directly from the data. Examples of the spectra for several of the galaxies that were not

TABLE 1

UPPER LIMIT MASS FACTORS FOR $\Delta V = 300$ km s^{-1}

Galaxy (NGC)	$3\,\sigma\langle T_A\rangle$ (K)	F ($10^6 M_\odot$ Mpc^{-2})	Notes	Galaxy (NGC)	$3\,\sigma\langle T_A\rangle$ (K)	F ($10^6 M_\odot$ Mpc^{-2})	Notes
1332..........	< 0.0089	< 2.0	a	4473..........	< 0.0092	< 2.2	
2768..........	< 0.01	< 2.4	b	4477..........	< 0.013	< 3.1	c
2784..........	< 0.0091	< 2.1		4494..........	< 0.0071	< 1.7	
2855..........	< 0.0091	< 2.1		4526..........	< 0.021	< 5.1	d
3115..........	< 0.0066	< 1.6		4594..........	< 0.010	< 2.5	
3377..........	< 0.0069	< 1.7		4621..........	< 0.011	< 2.5	
3489..........	< 0.014	< 3.3		4636..........	< 0.012	< 2.8	
3585..........	< 0.012	< 2.8		4697..........	< 0.012	< 2.8	
3998..........	< 0.0098	< 2.3		4753..........	< 0.012	< 2.8	
4274..........	< 0.013	< 3.1		4754..........	< 0.0081	< 1.9	
4278..........	< 0.011	< 2.7		4762..........	< 0.0081	< 1.9	
4314..........	< 0.017	< 4.0		5838..........	< 0.0088	< 2.1	
4429..........	< 0.014	< 3.4		5866..........	< 0.013	< 3.2	

NOTES.—(a) Formal 3 σ limit has been multiplied by 2 because of severe, large-scale baseline curvature. (b) Upper limit set by inspection; formal 3 σ limit is 0.023 K. (c) Formal limit multiplied by 1.42 to correct for data taken at wrong position. (d) Formal limit multiplied by 2.0 to correct for data taken at wrong position.

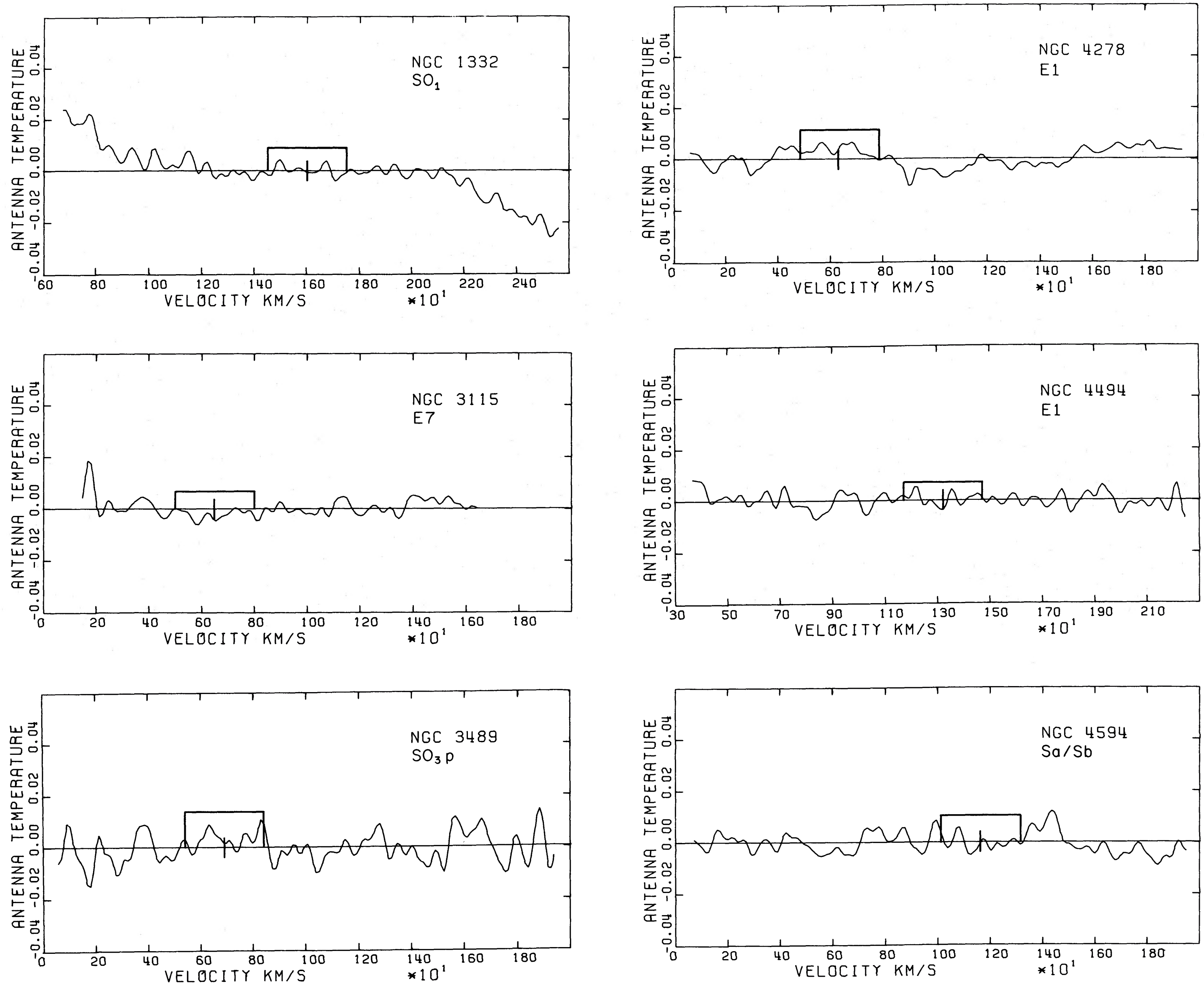

FIG. 1.—Representative spectra are shown for undetected program galaxies. The optical heliocentric velocities are marked, and a box has been drawn to represent the 3 σ upper limits to T_A as given in Table 1. The spectrum of NGC 1332 is a good example of the effects of baseline curvature. Also note the detection of NGC 3115 reported by Balkowski *et al.* would be nearly 3 times our upper limit.

TABLE 2

MASS FACTORS FOR DETECTED GALAXIES

Galaxy (NGC)	$\langle T_A \rangle$ (K)	ΔV (km s^{-1})	F ($10^6 M_\odot$ Mpc^{-2})
2685..........	0.024	306	5.8
4321*.........	0.055	270	12
5102..........	0.105	208	17

* Used as a standard to check system performance.

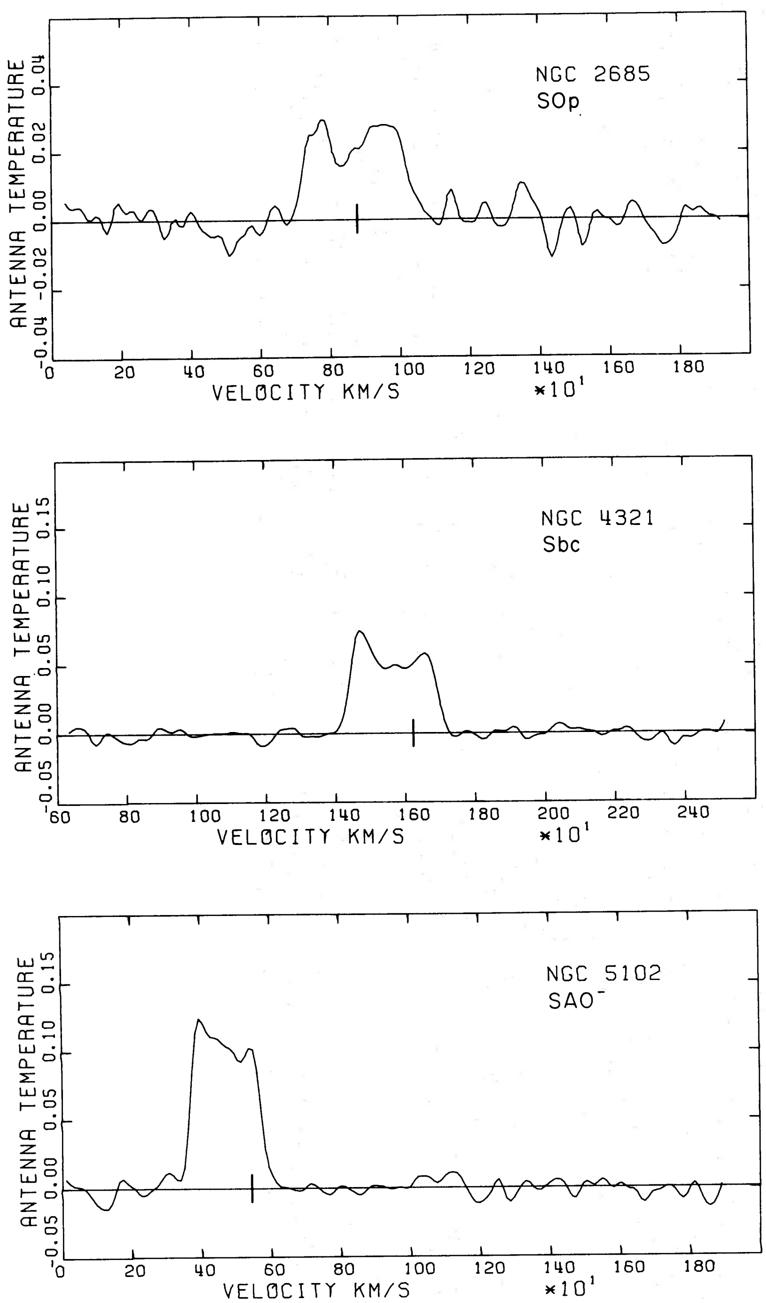

FIG. 2.—Line profiles are shown for the two detected S0 galaxies in Table 2. The profiles are typical of those found in later spirals, although somewhat less symmetrical. The heliocentric optical velocities are marked; this quantity differs slightly from the radio heliocentric velocity for NGC 5102. This galaxy is the best example of a system with a pure S0 form which contains H I. NGC 4321, an Sbc spiral, was used as a check on system performance.

detected are shown in Figure 1; the 300 km s^{-1} interval in which a signal might be expected is marked, and the 3 σ upper limit to T_A has been indicated. Figure 2 illustrates the spectra for the two detected S0 galaxies, NGC 2685 and NGC 5102, as well as data for the standard Sbc galaxy NGC 4321. Both of the S0 spectra have double-peak line profiles which are typical of the profiles found in spiral galaxies. Thus the H I is probably located in a rotating disk, although the disk may be much less extended than in normal galaxies (Bottinelli 1971).

The mass factors F given in Tables 1 and 2 can easily be converted to H I masses, provided that the distance to the galaxy is known; $M_{\rm H\,I} = {\rm F}D^2\,M_\odot$. In Table 3 we give $M_{\rm H\,I}$ and other data for all of the galaxies in our program. Morphological types are from Sandage (1974) unless otherwise noted. Radial velocities used to determine distances have been taken from the *Reference Catalog of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964) for field galaxies.[3] For galaxies contained in de Vaucouleurs (1975) groups, we have used the mean group radial velocity. Similarly, for galaxies listed as members of the Virgo cluster (de Vaucouleurs 1961), a mean cluster velocity has been adopted. All distances are based on these radial velocities and $H = 75$ km s^{-1} Mpc^{-1}.

Luminosities in column (7) of the table are from magnitudes measured on the Holmberg (1958) system. Most galaxies do not have Holmberg magnitudes, and a plot of $B(0)$ as given in the *Reference Catalog* versus Holmberg magnitude $m_{\rm Holm}$ for 50 early-type galaxies leads to the transformation for $10 \lesssim m_{\rm pg} \lesssim 13$,

$$m_{\rm Holm} = B(0) - 0.3\,. \qquad (3)$$

A statistical correction has been made for galactic extinction in computing both luminosities and colors. The proper form for such a correction is at present somewhat uncertain. The studies based on colors of galaxies at high galactic latitudes by Sandage (1972, 1973) tend to yield smaller values of A_B than might have been expected on the basis of galaxy counts (e.g., Noonan 1971; Burstein and McDonald 1975). We have chosen to use a conservative version of the cosecant law,

$$E(B - V) = 0.033 \csc |b|\,, \qquad (4)$$

and have taken the total B extinction to be given by $A_B = 4E(B - V)$. The colors based on $(B - V)(0)$ from the *Reference Catalog* and statistically corrected for extinction are the C_0' in column (6) of Table 3. Photographic luminosities $L_{\rm pg}$ in column (7) were calculated from the Holmberg magnitude corrected for extinction, the distances from column (4), and an absolute photographic magnitude for the Sun of 5.37 (Stebbins and Kron 1957). No correction has been made for inclination effects. Our luminosities are therefore very nearly on the same system as used by Roberts (1969), although slightly lower because of the reduced extinction and omission of inclination corrections. The implied optical masses M_* given in column (8) were computed by assuming $M_*/L_{\rm pg} = 25$ (10 for Sa's) in solar units for a typical early-type galaxy (King and Minkowski 1973).

[3] The V_0 in Tables 3 and 6 are velocities corrected for the solar motion relative to the Local Group of galaxies.

The last three columns of the table are based on H I masses found from the data in Tables 1 and 2. Column (9) lists $M_{\rm H\,I}$ in solar units, column (10) the distance-independent ratio $M_{\rm H\,I}/L_{\rm pg}$, and column (11) the ratio of $M_{\rm H\,I}$ to the estimated total mass. Since the hydrogen mass–optical luminosity ratio is derived directly from measured quantities, we shall use it preferentially in further comparisons between the optical and 21-cm properties of early-type galaxies which are presented later in the paper.

The lack of any detections among ellipticals in our sample is consistent with the results of earlier surveys (Gallagher 1972; Bottinelli *et al.* 1973; Guibert 1973; Knapp and Kerr 1974*a*); elliptical galaxies as a class appear not to have a significant mass fraction in the form of H I (Paper II). It is therefore reasonable to assume that the normal ellipticals represent a homogeneous set of objects, and the data in Table 3 may then be used to set an upper limit for $M_{\rm H\,I}/L_{\rm pg}$ for elliptical galaxies as a class. The mean H I mass for ellipticals has been calculated from $\langle M_{\rm H\,I}\rangle = \langle F\rangle\langle D^2\rangle$. Here $\langle D^2\rangle$ is simply the average of the distances squared. The mean mass factor $\langle F\rangle$ has been found from the 3 σ upper limit based on 33 km s^{-1} velocity intervals in an artificial spectrum based on the data from eight E galaxies (NGC 3115, 3377, 3585, 4278, 4636, 4621, 4494, 4697). This mean spectrum, illustrated in Figure 3, was produced by appropriately aligning and adding the individual spectrum for each galaxy weighted by its integration time. The same procedure was also used to find upper limits for S0 galaxies as a class. Data from six undetected S0 systems (NGC 2784, 3998, 4429, 4526, 5838, 5866) were combined to produce the spectrum in Figure 4. Table 4 lists the upper-limit H I masses for these mean E and S0 galaxies. Also included in the table are the two individual galaxies having the lowest measured individual ratios of $M_{\rm H\,I}/L_{\rm pg}$, NGC 4472 and NGC 4594.

III. INTERCOMPARISONS BETWEEN 21-CM OBSERVATIONS

Table 3 contains several galaxies for which 21-cm detections have been previously reported (see Table 5). However, we have failed to confirm some of these earlier results. For example, our observations agree with those given by Balkowski *et al.* (1972) for the mass of H I in NGC 2685 and NGC 5102, but our upper limits found for NGC 1332 and NGC 3115 fall well below their reported masses for these objects (see Figs. 1 and 2). In further discussions of H I in early-type galaxies, it is desirable to exclude such low-probability detections. Thus it is necessary to generate a selection criterion for the lower limit to the mass factor F which corresponds to a high-probability detection in the published lists of observations.

We have chosen such limits from an intercomparison between measurements of galaxies common to this and

TABLE 3

PROPERTIES OF PROGRAM GALAXIES

NGC (1)	TYPE [Source] (2)	V_o (3)	D_o (4)	m_{Holm} (5)	C'_o (6)	L_{pg} (7)	M_* (8)	M_{HI} (9)	M_{HI}/L_{pg} (10)	M_{HI}/M_* (11)
1332	$S0_1$	1497 $km\,s^{-1}$	20 Mpc	11.3	0.93	20 $\times10^9 L_\odot$	$5.0\times10^{11} M_\odot$	$<0.80\times10^9 M_\odot$	<0.04	$<2\times10^{-3}$
2685	S0p [1]	957	12.8	12.04+	0.80	4.4	1.1	0.95	0.22	9
2768	$S0_1$	1495	22.4(G41)	11.2	0.88	29	7.2	<1.2	<0.04	<2
2784	$S0_1$	431	7.1(G8)	11.2	0.95	3.9	0.98	<0.11	<0.03	<1
2855	$S0_3$/Sa(r)	1663	22.1	12.3	0.85	11	2.8	<1.0	<0.09	<4
3115	E7/$S0_1$ [1]	422	5.6	10.1	0.90	5.1×10^9	1.3×10^{11}	$<0.050\times10^9$	<0.01	$<0.4\times10^{-3}$
3377	E6	593	9.9(G11)	11.5	0.85	4.2	1.1	<0.17	<0.04	<2
3489	$S0^+$ [2]	57	9.9(G11)	10.9	0.55	6.8	1.7	<0.32	<0.05	<2
3585	E6	1240	16.5	11.1	0.89	18	4.5	<0.76	<0.04	<2
3998	$S0_1$	1177	15.7	11.5	0.91	10	2.5	<0.57	<0.06	<2
4274	Sa [1]	761	12.5(G13)	11.33+	0.90	7.4×10^9	$.74\times10^{11}$++	$<0.48\times10^9$	<0.06	$<6\times10^{-3}$
4278	E1	622	12.5(G13)	11.20+	0.89	8.4	2.1	<0.42	<0.05	<2
4314	SBap [1]	879	12.5(G13)	11.3	0.81	7.5	.75++	<0.63	<0.08	<8
4429	$S0_3$	1032	15.7(VIR)	11.09+	0.94	15	3.8	<0.84	<0.05	<2
4473	E5	2171	15.7(VIR)	11.3	0.85	12	3.0	<0.54	<0.04	<2
4477	$S0^+$	1194	15.7(VIR)	11.3	0.90	12 $\times10^9$	3.0×10^{11}	<0.76	<0.06	$<3\times10^{-3}$
4494	E1	1305	12.5(G13)	11.0	0.89	9.9	2.5	<0.27	<0.03	<1
4526	$S0_3$	396	15.7(VIR)	10.7	0.90	22	5.5	<1.3	<0.06	<2
4594	Sa/Sb [1]	1002	13.3	9.18+	0.93	64	6.4++	<0.44	<0.007	<.7
4621	E5	345	15.7(VIR)	11.0	0.96	16	4.0	<0.62	<0.04	<2
4636	E0	778	15.7(VIR)	10.6	0.88	23 $\times10^9$	5.8×10^{11}	$<0.69\times10^9$	<0.03	$<1\times10^{-3}$
4697	E5	1176	17.4(G20)	10.4	0.85	35	8.8	<0.85	<0.02	<1
4753	S0p [1]	1252	16.7	10.7	0.89	24	6.0	<0.78	<0.03	<1
4754	$S0^-$ [2]	1398	15.7(VIR)	11.5	0.91	10	2.5	<0.47	<0.05	<2
4762	$S0_1$ [1]	876	15.7(VIR)	11.2	0.79	13	3.3	<0.47	<0.04	<1
5102	$S0^-$ [2]	348	4.4(G4)	10.3*	0.53**	2.8×10^9	0.7×10^{11}	0.33×10^9	0.12	5×10^{-3}
5838	$S0_1$	1441	22.2(G50)	11.8	0.91	16	4.0	<1.0	<0.06	<3
5866	$S0_3$	972	12.3(G30)	10.9	0.82	10	2.5	<0.48	<0.05	<2

Notes to table 3:

Col. 2. Sources [1] Sandage (1961), The Hubble Atlas of Galaxies.

[2] de Vaucouleurs and de Vaucouleurs (1964), Reference Catalogue of Bright Galaxies.

All other types from Sandage (1974), private communication

Col. 4. Parenthesis refer to group memberships as given by de Vaucouleurs (1974) or Virgo cluster membership as given by de Vaucouleurs (1961).

Col. 5. + Magnitude from Holmberg (1958).

* Corrected m_H magnitude from the Reference Catalogue of Bright Galaxies.

Other magnitudes are corrected B(0) magnitudes from the Reference Catalogue.

Col. 6. ** Color from Alcaino (1974).

Col. 8. ++ For Sa galaxies M/L was assumed to be 10 in solar units.

TABLE 4

UPPER LIMIT MASSES FOR MEAN GALAXIES

Object	$\langle D^2 \rangle^{1/2}$ (Mpc)	$\langle F \rangle$	$\langle M_{\rm H\,I} \rangle$ ($\times 10^9 M_\odot$)	$\langle L_{\rm pg} \rangle$ ($\times 10^9 L_\odot$)	$\langle C_0' \rangle$	$\langle M_{\rm H\,I} \rangle / \langle L_{\rm pg} \rangle$
Mean of 8 Es.......	10.4	< 0.72	< 0.14	15	0.89 ± 0.03	< 0.0094
Mean of 6 S0s......	15.0	< 0.87	< 0.20	13	0.90 ± 0.05	< 0.0154
NGC 4472*........	15.7	< 0.61	< 0.15	74	0.91	< 0.002
NGC 4594.........	13.3	< 2.5	< 0.44	64	0.93	< 0.007

* H I data from Knapp and Kerr 1974*a*; $L_{\rm pg}$ derived from Holmberg's (1958) $m_{\rm pg} = 9.33$ and $D = 15.7$ Mpc.

four other surveys (Balkowski *et al.* 1972; Davies and Lewis 1973; Lewis and Davies 1973; Peterson and Shostak 1974). These data are shown in Table 5, from which we have chosen the detection criteria of $F \geqslant 7$ for the Balkowski *et al.* observations and $F \geqslant 12$ for the Jodrell Bank measurements. The Peterson and Shostak NRAO 300-foot (91 m) observations are probably of the highest quality, and have been used as basic standards for comparison with our observations. The measurements presented in Table 3 are in agreement with other data in the sense that detections are not found at levels above previously established upper limits. We therefore feel that our data reduction process has led to reasonable results.

Since none of the 21-cm observations (including those in the present paper) are made to a homogeneous sensitivity level, the above selection process can allow the worst case to set the lower limit for detections in each survey. It is therefore probable that some true detections will be discarded, and that galaxies with low intrinsic values of $M_{\rm H\,I}/L_{\rm pg}$ may be systematically overlooked. A good example of this is NGC 7625. The data of Balkowski *et al.* (1972) give $F = 3.7$, which is well below the adopted detection threshold of $F \geqslant 7$, but Peterson and Shostak find $F = 4.3$, and thus this galaxy must be considered as a true detection.

The set of early-type galaxies which can presently be regarded as having reliable 21-cm H I detections is given in Table 6. The format and techniques used to prepare this table are the same as those used for Table 3. Two active galaxies, NGC 1275 and NGC 5128, have unambiguous observations of H I in absorption against the nonthermal continuum, and have been included for completeness even though no estimates for $M_{\rm H\,I}$ are available. We have also felt it useful to include Irr II galaxies in the table, as the morphological division between an S0p and an Irr II galaxy is not very well defined (Krienke and Hodge 1974).

Several basic points follow immediately from a comparison between Table 6 and the numerous null results in Table 3: (1) No morphologically normal E galaxies have been observed to contain H I. However, both detected active galaxies are morphologically similar to ellipticals. (2) Some normal S0 galaxies contain considerable amounts of H I. A few of these differ little from undetected S0 systems in terms of colors. These results are further supported by the unpublished detections of the S0 galaxies NGC 2787, NGC 3626, and NGC 5631 by Roberts and Shostak (1974). (3) S0p and Irr II galaxies may contain large mass fractions of H I. However, such galaxies often have other indications (blue colors, dust, emission lines) of an extensive and active interstellar medium.

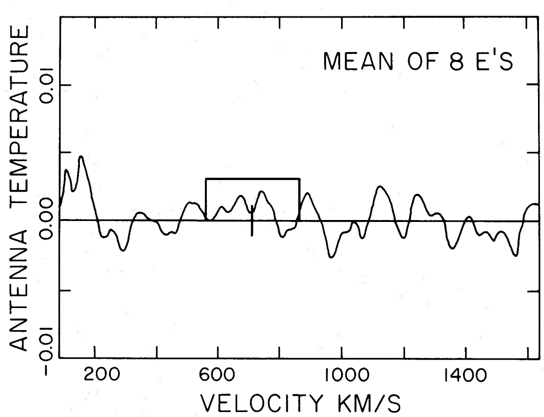

FIG. 3.—Synthetic spectrum for a mean E galaxy made by combining observations of eight individual ellipticals. The adopted 3 σ upper limit is also shown. To date no E galaxies have been detected and the mean H I content of this structural class must be very low.

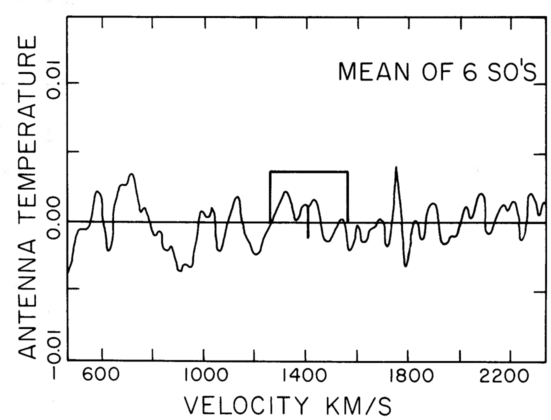

FIG. 4.—Synthetic spectrum for a mean undetected S0 galaxy made by combining observations of six individual S0's. To present levels of sensitivity, the H I properties of many S0's are indistinguishable from those of ellipticals.

TABLE 5

MASS FACTORS FROM DIFFERENT OBSERVERS*

NGC	Sources: This Paper	Balkowski et al. (1972)	Jodrell Bank†	Peterson and Shostak (1974)
IC 356	—	—	26	24
520	—	—	11	7
1023	—	6.7	—	4.6
1332	<2.0	5.0	—	—
2655	—	<1.7	11.2	—
2681	—	7.4	—	—
2685	5.8	6.7	< 8.3	8.2
3115††	<1.6	4.7	4.9	—
3227	—	1.7	4.0	—
3368	—	15	9.7	—
3448	—	—	14	15
3718	—	20	21	21
4151	—	5.9	15	—
4274	<3.1	—	9.1	—
4526	<5.1	—	6.6	—
4762	<1.9	—	< 3.6	—
4826	—	4.4	10.4	—
5102	17	25	—	—
6217	—	—	8.4	16
6340††	—	2.8	—	—
7625	—	3.7	—	4.3

* Table entries are F in $10^6 M_\odot$ Mpc^{-2}.

† Lewis and Davies (1973) and Davies and Lewis (1973).

†† Preliminary results from NRAO 300-foot by Roberts and Shostak (1974) indicate no signal

IV. H I CONTENT AND OTHER PROPERTIES OF GALAXIES

a) H I *and Optical Indicators of Interstellar Matter*

i) *Dust*

The detection of dark clouds on direct photographs is a sensitive test for the presence of interstellar material. In the Milky Way near the Sun, interstellar extinction and the column density of hydrogen atoms are correlated, and from estimates of the interstellar Lα absorption strength by Savage and Jenkins (1972) and from H I measurements by Knapp and Kerr (1974*b*), we adopt $n_{\text{H}} \approx 2 \times 10^{21} A_V$ atoms per cm^2. If we assume this relationship to be approximately correct for other galaxies, measurements of the amount of dust may provide a crude but useful independent estimate for the mass of interstellar gas.

We have therefore used blue photographs of galaxies in the *Hubble Atlas* (Sandage 1961) and the Lick Observatory plate files to make very rough estimates for $M_{\text{H I}}$ in some of the dustier galaxies studied here. Let $\langle A_V \rangle$ be the estimated mean extinction in dusty regions, X the obscured area in arcmin^2, and D the distance in Mpc; then

$$(M_{\text{H I}}/M_\odot)_{\text{dust}} = 1 \times 10^6\, X \langle A_V \rangle D^2\,. \qquad (5)$$

For all systems in our survey except NGC 4594, the above equation leads to $(M_{\text{H I}})_{\text{dust}} < 10^7\, M_\odot$. Since this mass is far below the observed upper limits, the presence of detectable dust in no way conflicts with the lack of observed neutral hydrogen in these galaxies. From Lick photographs of NGC 4594, we have set a conservative limit for the optical thickness of the disk perpendicular to its plane of $A_V \geq 0.5$, and have estimated the area to be about 27 arcmin^2. This leads to $(M_{\text{H I}})_{\text{dust}} \gtrsim 2 \times 10^9\, M_\odot$ as compared with the 21-cm limit $M_{\text{H I}} \lesssim 2 \times 10^8\, M_\odot$! Such a contradiction is simply a semiquantitative restatement of the fact that, on the basis of visual appearance, one would expect H I to be present in this galaxy.

Dust-free galaxies are also of interest. Elliptical galaxies (other than dwarf systems) are not observed to contain dust clouds and are also apparently devoid of H I. However, this correlation does not extend to S0 systems such as NGC 5102. From observations made with high spatial resolution, Balkowski *et al.* (1972) find an H I surface density of about 6×10^{-4} g cm^{-2}, which would imply from equation (5) $\langle A_V \rangle \approx 0.2$. The galaxy is relatively near, and one might therefore expect that some dust lanes or inhomogeneities would be observable. However, the *Palomar Sky Survey–Whiteoak Extension* prints, a 36-inch (91 cm) blue Crossley plate, and surface photometry by Sérsic (1969) all show a smooth brightness distribution. In NGC 5102, either the grain-to-gas ratio is much smaller than in the solar neighborhood, or the gas (and its associated dust) is exterior to the visible disk of the galaxy. This latter possibility seems unlikely, as Bottinelli (1971) has shown the H I to be concentrated toward the center of the galaxy.

ii) *Optical Emission*

Both the frequency of detection and characteristics of optical emission lines vary with galaxy type. The data concerning the relative proportions of galaxy samples showing detectable [O II] λ3727 have been summarized by Morgan and Osterbrock (1969); emission is found in about 15 percent of E galaxies and 30–50 percent of S0's, and is more common in later types. Not only is measurable emission less common in the early-type galaxies, but it may also result from different physical processes acting on the gas. Burbidge and Burbidge (1965) found that in E and S0 galaxies emission is more concentrated to the nuclear regions than in Sa or later spirals. In addition, the Hα/[N II] λ6583 ratio is usually less than 1 for early-type spirals, while in later spirals this ratio is reversed.

In the E and S0 galaxies, emission therefore appears to be primarily associated with processes in the nucleus of the galaxy. Indeed, strong emission lines such as those found in the radio galaxy NGC 4278 may be more closely correlated with the core radio source than the general state of the interstellar medium (Disney and Cromwell 1971). In all, 25 percent of the elliptical galaxies in Table 3 have emission recorded by Humason *et al.* (1956), and thus to the present levels of sensitivity, H I content and detectable optical emission lines are not correlated in E galaxies.

The observed sample of 16 normal S0 galaxies includes four Humason *et al.* emission-line systems; thus the set of S0 galaxies is also representative in

TABLE 6

SUMMARY OF HIGH PROBABILITY DETECTIONS

NGC	TYPE [Source]	V_o	D_o	m_{Holm}	C'_o	L_{pg}	F [Source]	M_{HI}	M_{HI}/L_{pg}	Notes
520	Irr II [1]	2320 km s^{-1}	31 Mpc	12.35	.71	18 $\times 10^9 L_\odot$	6.9 [PS]	$6.9\times10^9 M_\odot$	0.37	a,b*
1023	SBO [2]	729	7.5[G7]	10.48	.88	7.8	4.6 [PS]	0.26	0.033	a
1275	E2p [5]	5291	73 [PER]	12.8	.53	103	—	—	—	d,f,g
1291	SBO/a [2]	646	8.6	9.9	.88	13	>17[L]	1.3	0.10	b*,j
1326	SBO [2]	1381	18.4	11.5	.76	14	~6.6[BBGH]	2.2	0.16	c,b*,j
1808	SO/ap[2,5,7]	819	10.9	10.8	.85	10	17[BBGH]	2.0	0.20	b*,j
2685	SOp [1]	957	12.8	12.04	.80	4.4	8.2 [PS]	1.3	0.30	a
3034	Irr II [1]	322	2.1[G2]	9.20	.82	1.6	156[R69]	.69	0.43	a
3077	Irr II [1]	-26	2.1[G2]	10.57	.71	.45	59 [LD]	.26	0.58	a
3448	Irr II [3]	904	14.5[G28]	11.8	.40	6.7	15 [PS]	3.2	0.48	b,b*
3516	SBO: [2]	2777	37	12.6	.74	22	1.6[BBGH]	2.2	0.10	h
3718	SOp [1]	1128	14.3	11.24	.70	11	15 [R68]	3.1	0.21	a
4194	SBOp [2]	2684	36	12.5	—	21	1.1 [PS]	1.4	0.07	a
5102	SO [2,4]	348	4.4[G4]	10.3	.53	2.8	17 [GFB]	0.33	0.12	i
5128	Ep [8]	271	4.4[G4]	7.87	.88	30	—	—	—	a,c
7625	SOp, Irr II? [6]	2009	27	13.2	.69	6.7	4.3 [PS]	3.1	0.46	

Notes to Table 6:
a) Magnitude from Holmberg (1958). Other magnitudes from B(0) given in Reference Catalog corrected to the Holmberg system. Also see notes b, and j.
b) Magnitude (b* colors) from de Vaucouleurs and de Vaucouleurs (1972) corrected for aperture effects using data in the Reference Catalog.
c) Radial velocity from Bottinelli et al. (1970).
d) HI found in both emission and absorption; no mass estimates (Roberts 1970, Whiteoak and Gardner 1971).
e) HI absorption found by De Young, Roberts, and Saslaw (1973).
f) Mean velocity for Perseus cluster from Chincarini and Rood (1971).
g) Color from Sandage (1973).
h) HI detection confirmed by Roberts and Shostak (1974); Seyfert galaxy.
i) Color from Alcaino (1974).
j) Magnitude from corrected Harvard magnitude in the Reference Catalog.

Sources for types [1] Sandage (1961); [2] de Vaucouleurs and de Vaucouleurs (1964); [3] de Vaucouleurs and de Vaucouleurs (1972); [4] Sandage, Freeman, and Stokes (1970); [5] Morgan (1958); [6] Demoulin (1969); [7] Arp and Bertola (1970); [8] Holmberg (1958).

Sources for F: [PS] Peterson and Shostak (1974); [L] Lewis (1970); [BBGH] Balkowski et al. (1972); [R69], [R68] Roberts (1969, 1968); [GFB] this paper; [LD] Lewis and Davies (1973).

terms of the fraction with emission lines. Again, there is no correlation between optical emission and H I masses, since there is no emission in either NGC 1023 (Humason *et al.* 1956) or NGC 5102 (see below).

Among the Irr II and S0p galaxies, optical line emission is much more common than in the normal S0's. Of the detected galaxies in Table 6, only one, NGC 520, does not have general optical emission (Krienke and Hodge 1974 and references therein). There are no data for NGC 4194. The rest, however, are listed by either Krienke and Hodge or Humason *et al.* as being emission-line objects. Comparing the H I data in Tables 3 and 6 with the tabulation of properties by Krienke and Hodge, one finds that all three of the "explosive" Irr II galaxies surveyed (NGC 3077, 3034, 4691; Roberts and Shostak 1974) contain H I. The other active galaxies NGC 1275, NGC 1808, and NGC 5128 should probably also be considered in this class. Two out of the three tidally interacting systems have been observed at 21 cm, and both contain H I. Only the "dusty" galaxy NGC 4753 was not detected. The peculiarities related to NGC 2685, NGC 3718, and NGC 7625 are uncertain, although NGC 2685 and NGC 3718 have some indications of spiral structure and may therefore be related to later spirals. We therefore feel that the connection among peculiar galaxies is not necessarily one between optical emission and H I content, but one between disturbed galaxies and H I content.

We have also checked for possible correlations between observable H I and the number of distinct H II regions, n(H II). Using n(H II) from Chromey (1974) and from Hodge (1969, 1974), we have plotted n(H II) versus H I content for the galaxies discussed in this paper, in Balkowski *et al.* ($F \geq 7$), and in Roberts (1969). No simple relationship is found. However, in the present sample (which admittedly contains mainly Sb or later type galaxies), all systems having n(H II) ≥ 1 do contain H I. The converse is not true; n(H II) $= 0$ does not imply small H I, as is shown for example by the S0 galaxy NGC 5102 or the Sa galaxy NGC 2681, which has $M_{\rm H\,I}/L_{\rm pg} = 0.14$ (Balkowski *et al.* 1972). However, it is interesting to note that NGC 4594 is devoid of both H II regions (Münch 1962; Chromey 1974) and H I, despite the apparent presence of knots of blue stars (Lindblad 1951).

iii) *Summary*

The possible relationships between the presence of optically observable interstellar matter in the form of dust in dark clouds or lanes, diffuse ionized gas, or distinct H II regions and interstellar H I remain confused in the early-type galaxies. On the one hand, NGC 4594 has large amounts of dust and yet does not contain either H II regions or H I to relatively strict limits. At the other extreme, NGC 5102 contains neither ionized gas nor dust, and yet has a considerable amount of H I. It is also likely that, at least in structurally normal E and S0 galaxies, the presence of nuclear optical emission is not related to total H I content. We therefore suggest that a lack of coupling between optical features and detectable H I may be common among all structurally normal early-type galaxies. One speculation is that this decoupling in normal galaxies is caused by the absence of spiral arms, which are known to be important in determining the distribution of both dust lanes and H II regions in normal later type spirals (e.g., Lynds 1972).

Many of the morphologically peculiar systems in our study are classified by Krienke and Hodge (1974) as "explosive" or "tidally interacting" Irr II's. If we add NGC 1275, NGC 1808, NGC 3516, and NGC 5128 to this group, it becomes possible to argue that violently disrupted galaxies are rich in H I. For some of the Irr II's, it is possible that the present large H I content is a result of gas captured during close collisions with other galaxies (e.g., NGC 5253 or NGC 5195). In the present program, the only sample of a Krienke and Hodge "dusty" galaxy, NGC 4753, was not detected.

b) H I *and the Stellar Population*

The morphological sequence of galaxies is in some respects an approximate ordering of galaxies in terms of the dominance in optical light by different combinations of stellar populations (see King 1971). This is most clearly embodied in the Yerkes classification system, which is based on an empirical correlation between optical form and blue spectral type (Morgan and Mayall 1957; Morgan and Osterbrock 1969 and references therein), but it was also found in the close relationship between color and type for galaxies classified on other systems (e.g., de Vaucouleurs and de Vaucouleurs 1972). A statistical correlation also exists between H I content and galaxy type or color, although most of the observations refer to spirals of class Sb and later (Roberts 1969, 1972). A fairly large sample of Sa galaxies is listed by Balkowski *et al.* (1972), but, because of the problems concerning the reliability of their detections discussed above, we have not included these galaxies in this section. The omission of Sa galaxies should not have a major effect on our conclusions.

For the galaxies in Tables 3 and 6 we have three possible sources for estimating the stellar content: Humason *et al.* spectral types, Yerkes form classifications, and the corrected $B - V$ colors, C_0'. Since $B - V$ colors can provide considerable insight into the type of stellar population (Searle *et al.* 1973; Larson and Tinsley 1974) and are available for most of the program galaxies, we first consider the correlations between H I content and C_0'. Spectral types and Yerkes classes will be used as an additional check on conclusions based on colors.

The C_0' used in this paper are $B - V$ colors corrected for galactic reddening using the cosecant extinction law from equation (4). Since this gives a smaller correction than most extinction laws based on galaxy counts, the C_0' can be expected to be redder than mean colors given by de Vaucouleurs and de Vaucouleurs (1972). From a sample of six S0 and eight E galaxies in Table 4, we find this difference to be at most 0.05 magnitudes.

Figure 5 displays the observed relationship between C_0' and $M_{\rm H\,I}/L_{\rm pg}$ for a sample of Sb and earlier type galaxies. Colors and $M_{\rm H\,I}/L_{\rm pg}$ for the E, S0, S0p, and Irr II galaxies are from Tables 3 and 6, while the Sb and Sc spiral data are based on Roberts's (1969) lists. We have computed C_0' colors for the Sb and Sc galaxies, again making no inclination corrections, but have taken the $M_{\rm H\,I}/L_{\rm pg}$ ratios directly from Roberts. In addition to interesting individual galaxies, means for detected Sb's and Sc's as well as upper limits for a mean E and S0 from Table 4 are also plotted.

Figure 5 has several interesting features. Most notable is the spread in colors among the detected S0 galaxies. These galaxies have colors which range from as blue as an Sc for NGC 5102 to indistinguishable from a typical E for NGC 1291 and NGC 1023. We also find that there is a major change in both the slope and dispersion of the mean C_0'–$M_{\rm H\,I}/L_{\rm pg}$ relationship for $C_0' > 0.8$. The very low upper limits for H I in NGC 3115, NGC 4472 (Knapp and Kerr 1974*a*, not plotted), and NGC 4594 place these galaxies well below an extrapolation of the mean C_0'–$M_{\rm H\,I}/L_{\rm pg}$ relationship for Sb and Sc spirals. However, another undetected galaxy, NGC 3489, has blue colors, but is hydrogen-deficient (photometry by Lasker 1970 confirms the blue colors, but suggests that $B - V$ may be greater than the value of 0.55 used here). We also note that the correlation between H I content and color which is found for Sb and later spirals (Roberts 1969) may not extend to the detected (i.e., H I-rich) S0 galaxies.

The S0p and Irr II galaxies as a class have excess H I for their colors. This may partially be a result of failing to allow for internal reddening when the colors were computed. However, from an examination of photographs of these galaxies, it seems uncertain as to whether dust could provide the required 0.3 to 0.4 magnitudes of reddening. It would appear to be equally likely that these types of galaxies simply have different intrinsic characteristics than morphologically normal systems.

We have also checked Humason *et al.* (1956) spectral types and Yerkes form classes (Morgan 1958, 1959) for possible relationships between stellar populations and H I content. The mean spectral types for the undetected E and S0 galaxies are G5 $\pm$ 2 and G3 $\pm$ 1, respectively. Among normal galaxies containing H I, NGC 1023 is type G5 and NGC 5102 has an A or early F spectrum. For the rest of the normal S0's, no spectral types are available.

The peculiar colors of NGC 5102 were first noted by Freeman (Eggen 1971). Both his observations and the photometry from Alcaino (1974) indicate that the

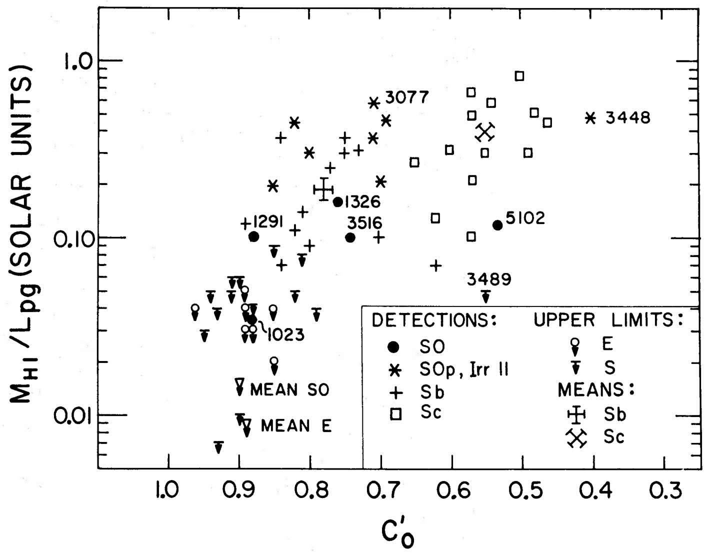

FIG. 5.—The observed relationship between color and H I content is shown for Sc and earlier Hubble types. The detected structurally normal S0 galaxies show a considerable range in color; NGC 5102 is as blue as an Sc but NGC 1291 has the C_0' of an E. NGC 3489 may be an example of a blue galaxy which is deficient in H I. The peculiar galaxies have excess H I for their colors when compared with normal spirals. Note that most of the upper limits for S galaxies refer to the S0's in Table 3.

nuclear regions of the galaxy are unusually blue. This was attributed by Freeman to the presence of an unusually metal-poor stellar population. We therefore obtained green-region spectra with the IT-ID spectrum scanner on the Lick 120-inch (3 m) telescope for both the nucleus and a point 8″ southwest in the disk. Figure 6 shows spectra of NGC 5102 and, for comparison, a nuclear-region spectrum of the normal S0 NGC 4762. Because of the low declination ($\delta = -37°$), atmospheric refraction is important, and we are uncertain as to exactly where the galaxy was sampled. Furthermore, the red and blue parts of the spectra do not refer to the same positions, and the continuum energy distributions are therefore not meaningful. The strength of Hβ indicates that a significant fraction of light is contributed by F or earlier stars. Despite the low signal-to-noise of the disk measurements and the refraction problems, our data show the hydrogen line to be weaker in the disk than in the nucleus. Since Alcaino used only a 22″ diaphragm, it is likely that the true $(B - V)(0)$ color (which would include more light from the disk) is redder than that used here.

Freeman compares the spectrum with that of M5, a metal-poor globular cluster. However, the present observations suggest that the weakness of the metal features is primarily due to the large continuum contribution from hot stars. The great strength of Hβ indicates that roughly half the light near 5000 Å comes from stars of type F and hotter. If so, the strengths of MgH, Mg *b*, and Na D are about what one would expect in a normal elliptical of this luminosity. Since NGC 5102 does not appear to be metal-poor, the A-type spectrum is evidence not for a hot horizontal branch, but for a young stellar component in the nucleus. It is interesting to speculate that if most of the dust were to be blown out of a nucleus resembling, for example, that in NGC 1808 (Osmer *et al.* 1974), the remaining nuclear region might closely resemble NGC 5102, with a luminous core of younger stars being all that remains of the previous active stage.

Among the peculiar systems, NGC 2685 and NGC 3718 have relatively normal G spectral types, while NGC 3034 is A5 and NGC 5128 is F8. NGC 7625 is classified as G in Humason *et al.*, but Demoulin (1969) has shown the blue spectral type to be much earlier, perhaps about A. Thus the light contribution from young stellar populations in the peculiars is more pronounced in the color measurements (which refer to light from a large fraction of the galaxy) than in the few available spectra of nuclear regions.

The Yerkes form types give similar results. Galaxies which were not detected were primarily placed in form class k, although a few systems were classified as gk. Only NGC 1023 and NGC 1326 were classified among the normal detected galaxies; NGC 1023 is a kDp and NGC 1326 is kB?. The Irr II and S0p galaxies in Table 6 were assigned form classes ranging from kDp for NGC 2685 to aI for NGC 3034; some possible implications of this spread in Yerkes class among the Irr II galaxies have been discussed by Krienke and Hodge (1974).

In summary, we find from the present limited sample of normal early-type galaxies no obvious correlations between young stellar populations and H I content. That is, although NGC 5102 and NGC 1291 contain detectable H I, NGC 5102 has a blue nuclear region, while NGC 1291 has colors close to those found in elliptical galaxies. A simple interpretation is that the presence of considerable amounts of H I is not in itself a necessary condition for extensive star formation. Conversely, there exist galaxies such as NGC 3489 which have relatively blue colors but are deficient in H I.

Most peculiar galaxies both are rich in H I and show

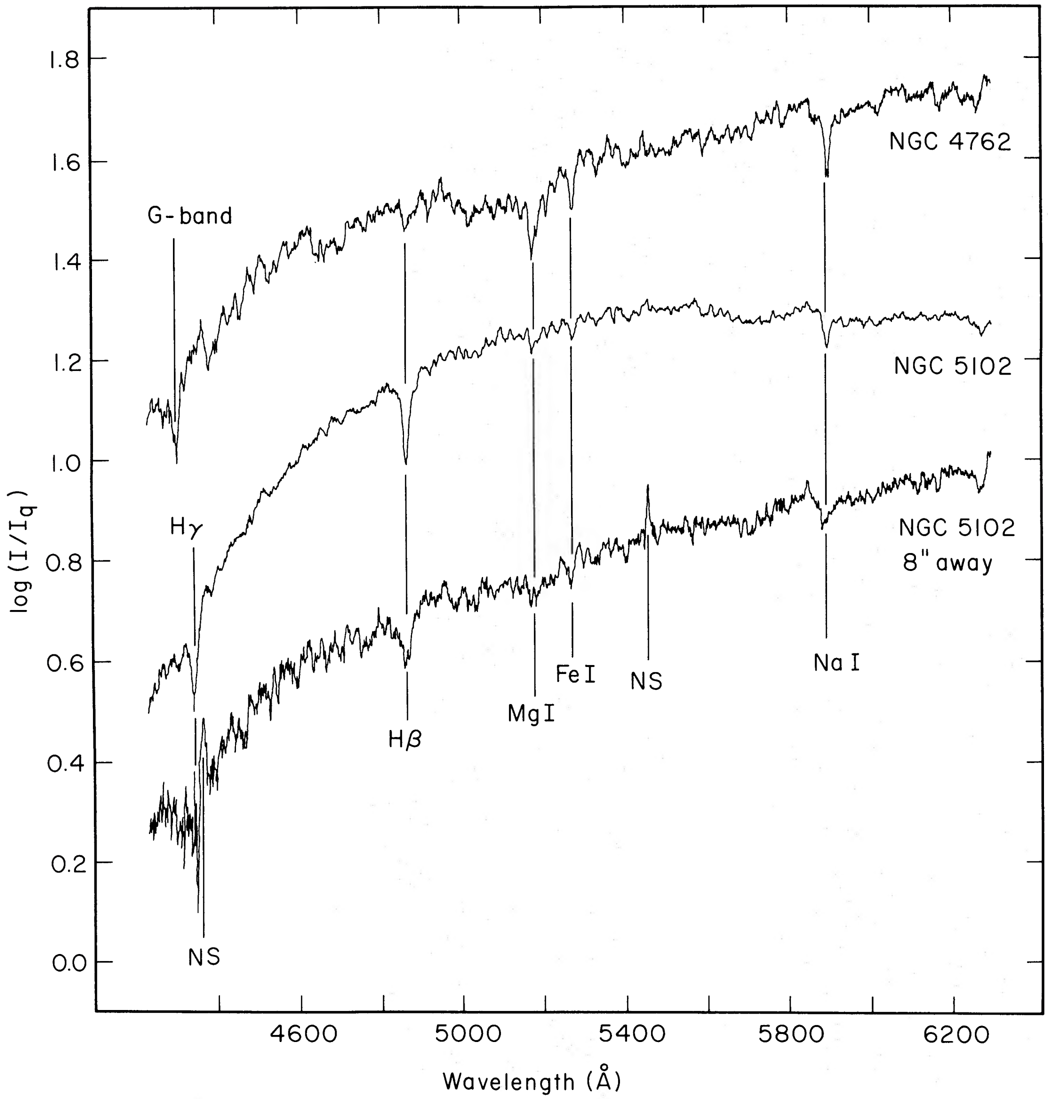

FIG. 6.—Spectra obtained with the Lick IT-ID scanner are shown for the disk and nucleus of NGC 5102 and for the nuclear region of the normal S0 NGC 4762. The weakness of the metal absorption lines in NGC 5102 is primarily due to the large light contribution of F or earlier stars. Note the absence of emission lines in NGC 5102.

evidence for recent star formation. The colors are probably strongly affected by internal reddening, and thus the extent of the young stellar component is difficult to assess. However, given the extensive presence of dust, H I, and young stars, it is probable that many Irr II and S0p galaxies simply contain more interstellar matter than other early-type galaxies. NGC 4753, on the other hand, seems to be closely related to other undetected S0 galaxies except for the presence of an unusually large amount of dust.

c) H I *Content and the Hubble Sequence*

In attempting to understand the significance of the structural sequence of galaxies, considerable effort has been applied to searching for correlations between physical properties and galaxy class (e.g. Sandage *et al.* 1970). One of the better correlations has been found for H I content versus Hubble type primarily among the Sb and later spirals (Roberts 1969, 1972). More recently, Balkowski *et al.* (1972) and Lewis and Davies (1973) have observed Sa and S0 galaxies in an effort to extend this relationship to cover all disk-dominated galaxies. Both of these studies concluded that the rate of decrease of $M_{\rm H\,I}/L_{\rm pg}$ becomes smaller for earlier types, and that the relative H I content may even increase slightly for the S0 class. There are, however, serious problems concerning the reliability of the H I masses from these surveys (see Table 5). In addition, several morphologically peculiar galaxies such as IC 356 (Lewis and Davies) or NGC 2685 (Balkowski *et al.*) are included in the sample of normal galaxies. Since, as we have shown above, the peculiar galaxies have systematically high H I content, this also

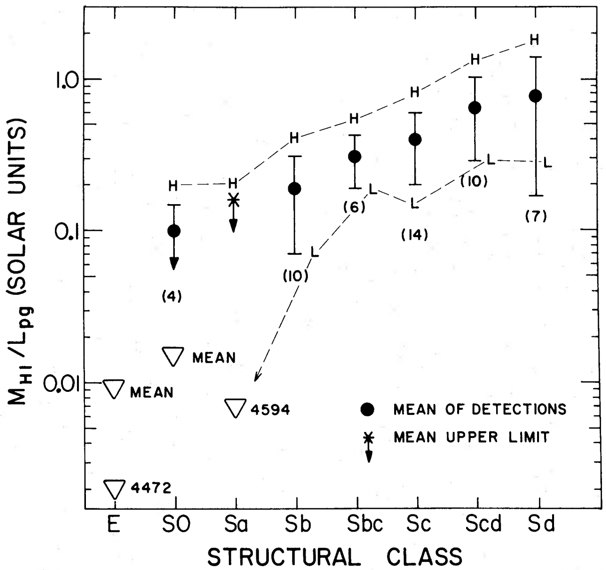

FIG. 7.—H I content is shown for Hubble classes Sd and earlier. Data for types Sb-Sd are from Roberts (1969), the mean upper limit for Sa's is from Balkowski *et al.* as discussed in the text, and the E and S0 data are from Tables 4 and 6. Error bars refer to the dispersions in the samples and high and low measurements for each class are indicated. The S0's appear to be a true transition between the H I properties of later spirals and those of ellipticals.

will lead to an overestimate of the amount of H I found in S0 and other early-type galaxies.

Figure 7 shows the distance-independent ratio $M_{\rm H\,I}/L_{\rm pg}$ for the Sd and earlier type galaxies. The data for the Sb–Sd types were taken directly from Roberts's (1969) compilation. Since the luminosities used here will tend to be slightly lower than those of Roberts, the drop between classes Sa and Sb is in reality slightly larger than shown in the figure. The mean for detected Sa galaxies is $M_{\rm H\,I}/L_{\rm pg} = 0.12$, but it is based on only two structurally normal galaxies in Balkowski *et al.* which meet our selection criterion $F \geqslant 7 \times 10^6 M_\odot$ $\rm Mpc^{-2}$, NGC 2681 and NGC 3368. The mean upper limit in Figure 7 was therefore found by taking all the measurements by Balkowski *et al.* of normal Sa's at face value and averaging. The point for detected S0 systems refers to observations in Table 6. We have also noted the extreme ranges for each type by using the highest and lowest observed $M_{\rm H\,I}/L_{\rm pg}$ from the various lists as well as some relevant upper limits from Tables 3 and 4. To our knowledge no Sb or later galaxies have been observed to have $M_{\rm H\,I}/L_{\rm pg} \leqslant 0.05$, which is a representative value for the upper limits in Table 3.

The H I content–structural class relationship is a broad ridge across Figure 7, decreasing by about a factor of 10 between types Sd and Sb. For this range of types, which includes galaxies with dominant spiral arms, $M_{\rm H\,I}$ is always at least $\sim 0.1\, L_{\rm pg}$ in solar units. At the other extreme are the E galaxies which have $M_{\rm H\,I} < 0.05\, L_{\rm pg}$ (and probably $< 0.01\, L_{\rm pg}$). In terms of H I content, the S0 and Sa classes seem to form a transition between spirals with arms and pure ellipticals. Although the samples are still very small, at least some fraction of the S0 and Sa galaxies have H I masses comparable to those found in the lower ranges of the Sb and even the Sc classes. Other S0 galaxies such as NGC 3115 or NGC 2784 have upper limits comparable to those found for the ellipticals. The data in Table 4 also show the synthetic mean undetected E and S0 galaxies to be virtually indistinguishable in terms of either colors or H I content. Finally there is NGC 1023, which is at present the only example of a galaxy containing detectable H I, even though the H I content is significantly less than has been found in an Sb.

Given this range in H I properties, a mean point for S0 galaxies is not easily defined. If the data in Tables 3 and 6 are taken at face value and averaged, then the mean $M_{\rm H\,I}/L_{\rm pg}$ for the S0 class as represented by 18 galaxies is less than 0.06. *Thus we find, in contrast to the earlier discussions by Balkowski et al. and by Lewis and Davies, that $M_{\rm H\,I}/L_{\rm pg}$ continues to decrease smoothly through the* S0 *class.* The mean H I content of the Sa galaxies is subject to similar uncertainties, but the present sample is too small to allow a meaningful average to be made. A break in basic H I properties occurs between the elliptical and S0 classes, although large and time-consuming surveys to very low signal levels will be required if the detailed differences between S0's and E's are to be understood. It would be of particular importance to establish (1) whether all galaxies having disks contain H I, and (2) if the upper limit for NGC 4472 is representative of non–Virgo Cluster E's.

V. SUMMARY

Several major points concerning the nature of early-type galaxies follow from the results of the present study:

1. Elliptical galaxies contain less than about 0.1 percent H I by mass. Furthermore, this upper limit is conservative, and the stronger constraint placed on the H I content of NGC 4472 by Knapp and Kerr (1974*a*) of $M_{\rm H\,I}/M \leqslant 10^{-4}$ is probably more nearly representative of normal ellipticals. The observed fossil stellar populations (Larson and Tinsley 1974), the lack of dust clouds, the low H I masses, and the concentration of optical emission to the nuclear region all support the hypothesis that these galaxies are devoid of interstellar matter at the densities found in later-type spirals.

2. Morphologically normal S0 galaxies exist with $M_{\rm H\,I}/L_{\rm pg} \geqslant 0.05$ ($M_{\rm H\,I}/M \geqslant 2 \times 10^{-3}$). Other apparently similar galaxies are observed to have smaller upper limits for $M_{\rm H\,I}$, but the present sample is too small to determine the relative fractions of hydrogen-rich and hydrogen-poor S0's. However, for normal S0's, the presence or absence of detectable H I does *not* seem to correlate with other indicators for interstellar matter such as dust lanes, optical emission lines, or even blue colors (e.g. NGC 3489). Some detected S0 galaxies are indistinguishable from normal ellipticals on the basis of $B - V$ colors.

3. Many galaxies which could be classified as active systems (explosive Irr II, interacting galaxies, etc.)

both are morphologically peculiar and have systematically large amounts of H I. Unlike the normal S0's, these galaxies often have obvious features due to young stars. The only two nonactive peculiar galaxies observed, NGC 4314 and NGC 4753, were not detected.

4. The S0 class of galaxies appears to form a true transition between the H I properties of spirals and ellipticals. Our small sample of galaxies contains both spiral-like systems with $M_{\rm HI}/L_{\rm pg}$ ratios that would not be outside the observed range for Sb's, and elliptical-like galaxies with only an upper limit for $M_{\rm HI}$. NGC 1023 is at present the only normal galaxy known which has an $M_{\rm HI}/L_{\rm pg}$ ratio that is significantly lower than is found in Sb spirals.

5. In several galaxies, interstellar matter is present but has unusual properties. A massive dusty disk is seen in NGC 4594, but no H I is found. Another case is NGC 5102: young stars dominate the nuclear region, yet no optical emission is detected, and there is no evidence for dust. Clearly these are different circumstances than are found in spiral galaxies, where H II regions, dust, young stars, and H I are all closely related.

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