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H I IN EARLY-TYPE GALAXIES. III. OBSERVATIONS OF S0 GALAXIES*

BRUCE BALICK AND S. M. FABER
Lick Observatory and Board of Studies in Astronomy and Astrophysics,
University of California at Santa Cruz

AND

J. S. GALLAGHER
School of Physics and Astronomy,
University of Minnesota
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ABSTRACT

Observations of H I in 17 selected early-type galaxies (predominantly S0) are reported. Nearly half have been detected. The H I mass-to-light ratio $M_{\rm H\,I}/L_{\rm pg}$ is roughly correlated with galaxy color (based on $B-V$ photometry) but not with other characteristics of these galaxies. Morphologically normal S0 galaxies display the same general trend between $M_{\rm H\,I}/L_{\rm pg}$ and color as that followed by normal galaxies along the Hubble sequence and by peculiar and Irr II galaxies as well.

Subject headings: galaxies: structure — interstellar: matter — radio sources: 21 cm radiation

I. INTRODUCTION

At opposite ends of the Hubble sequence lie galaxies dominated by stellar systems of spherical or elliptical symmetry and galaxies in which the stars, gas, and dust are primarily confined to a disk. Several properties of galaxies, such as the prominence of the disk, the integrated colors, and the fractional gaseous content, appear to vary regularly along the Hubble sequence, at least in broad terms. However, considerable scatter is usually present in these relationships, and individual galaxies often deviate markedly in their properties from others having the same morphological type.

It is known that the early-type galaxies, taken as a group, are deficient in dust and gas relative to later types, and it is often suggested that, as a result, the rate of star formation is considerably smaller in these earlier systems. The amount of gas is generally determined by observations of the 21 cm H I line, although weak optical emission from ionized species such as [O II] λ3727 is sometimes present as well. In the earliest galaxies, little or no H I whatsoever can be detected with present equipment, and studies of the neutral gaseous content of early galaxies must be made at slightly later types, where H I can occasionally be seen. This marginally detectable morphological type is presently the S0 class.

Recent 21 cm observations of early-type galaxies have been made by Gallagher, Faber, and Balick (1975, hereafter Paper I), Lewis and Davies (1973), Balkowski *et al.* (1972), Roberts (1969, 1972), Huchtmeier, Tammann, and Wendker (1975), and Shostak *et al.* (1975), among others. Faber and Gallagher (1976, hereafter Paper II) have investigated whether the gas can be present in forms other than H I. They conclude that this possibility is not likely, and that since an appreciable mass inflow rate from evolved stars is to be expected, a mechanism must exist for removing gas from the galaxy or at least making the gas impossible to detect.

In this paper we report additional observations of 21 cm H I lines in early-type galaxies, primarily S0s. Seventeen galaxies were carefully selected for observation on the basis of their colors, photographic appearance, or other factors which we speculated might enhance the possibility of detecting gas in them. As a control sample, some of the selected galaxies were morphologically normal and had normal colors. Nearly half of the program galaxies were detected. The observations and results are discussed in § II, and the properties of individual galaxies are summarized in the next section. Relationships between H I content and other observable properties of this class of galaxies are explored in § IV.

II. OBSERVATIONS AND RESULTS

The observations were performed at the 140 foot (43 m) telescope of the National Radio Astronomy Observatory[1] in 1975 August. Two receivers having a system temperature of ~50 K were used in conjunction with dual 192 channel line receivers, each of which was centered at the same center velocity and had a total bandwidth of ~2000 km s^{-1}. The total integration time varied among the galaxies depending on a variety of criteria including detected line temperature or upper limit, time above the horizon, and the availability of other galaxies. The data were

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

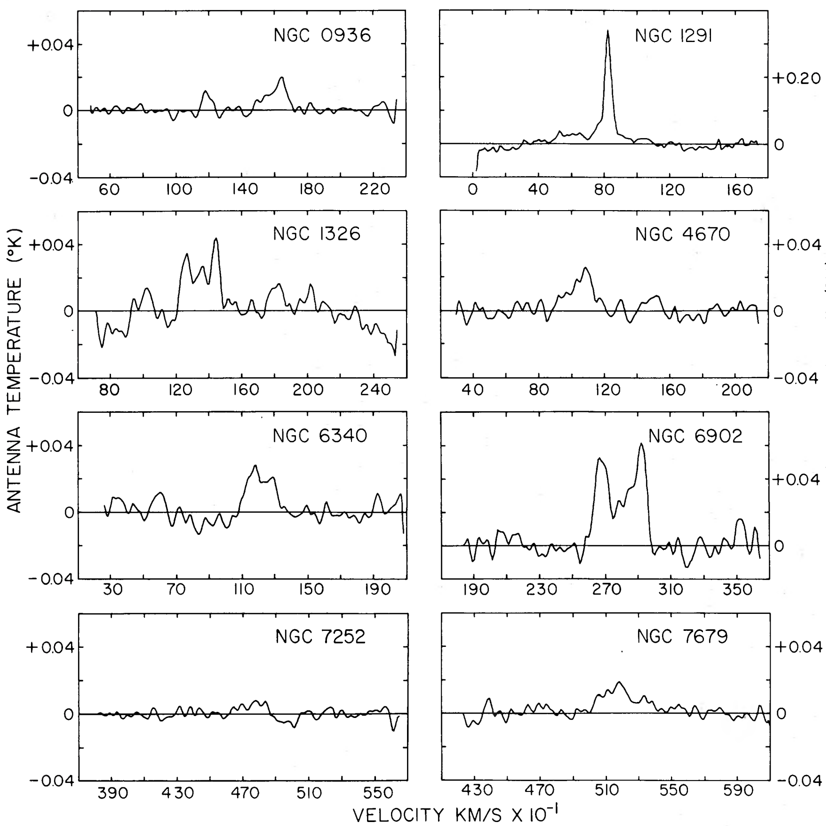

FIG. 1.—Spectral scans of detected galaxies. NGC 7252 may exhibit a weak feature below the adopted upper limit for detection.

acquired and reduced in the manner described in Paper I. The beam full width at half-maximum (FWHM) is 20′; a signal of 1 K corresponds to a radio flux density of 3.36 Jy.

The ability to detect 21 cm emission in these galaxies is generally limited by spurious spectral features of about the same shape as the line of interest, as discussed in Paper I. These features seem to be caused by instabilities in the telescope or receiver performance. Past experience indicates that the system stability is best at night, so the present observations were conducted only between 16^h and 3^h local sidereal time. Because the telescope tracks over hour angles of up to 7^h from zenith, most, but not all, of the galaxies could be observed for at least 1 and as much as 11 hours per day. During our observations, the observing system was generally very stable, and any data in which evidence of confusing baseline ripples could be seen were rejected. Very few data were discarded, however, except for some scans of galaxies observed at very low elevation angles.

The individual scans of each galaxy were averaged together, and the composite spectra were then smoothed over three channels (33 km s^{-1}) and a linear baseline removed. Including the SBbc galaxy NGC 6217, which was a test case of a weak but previously detected galaxy (Lewis and Davies 1973; Peterson and Shostak 1974), eight of the 18 observed galaxies exhibited spectral features within ~100 km s^{-1} of the optical velocities taken from the *Reference Catalogue of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964) or in the cases of NGC 936 and 6340, measured by Faber using the 120 inch (3.1 m) telescope of the Lick Observatory. Line profiles of the detected galaxies are shown in Figure 1.

III. INDIVIDUAL GALAXIES

In this section we discuss characteristics of the individual galaxies observed. The observed hydrogen mass for detected galaxies is given by $M_{\text{H I}} = 0.8D^2 \int T_A dV \times 10^6 M_\odot$, where D is the distance to the galaxy in megaparsecs and $\int T_A dV$ is the integral over the line profile. Line profiles for detected galaxies are shown in Figure 1. In discussing the H I content, we normalize the hydrogen mass $M_{\text{H I}}$ to the photographic luminosity L_{pg} of the galaxy (on Holmberg's system) and abbreviate the ratio as H I/L. Observed upper limits to this ratio depend on distance because of different limitations in the determination of $M_{\text{H I}}$ and L_{pg}. Values of H I/L are shown in Table 1, along with other observable parameters of the galaxies, whose meanings were reviewed in Paper I. We also list $\sigma(T_A)$, the channel-to-channel rms deviations of each profile after smoothing to 33 km s^{-1}. In all

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TABLE 1

PROPERTIES OF PROGRAM GALAXIES

NGC (1)	TYPE (2)	V(HI) (3)	V(opt) (4)	D_o (5)	m_{Holm} (6)	C'_o (7)	L_{pg} (8)	M_{HI} (9)	M_{HI}/L_{pg} (10)	$M_{HI}/\sigma(M)$ (11)	$\sigma(T_A)$ (12)	Notes (13)
						Detected Galaxies						
1291	SB0/a[1]	835	802	8.6Mpc	9.87	0.88[5]	13 x $10^9 L_\odot$	1.3 x $10^9 M_\odot$	0.10	9.3	.0137	A
1326	SB0$^+$[1]	1360	1381	19.5(G53)	11.45	0.76[5]	15	1.8	0.12	4.0	.0053	B
4670	SB0/ap[1]	1049	1210	12.5(G13)	13.14	0.36[1]	1.4	0.49	0.35	3.4	.0041	D
6340	SB0/a[1]	1193	1251	23.6(G51)	11.91	0.86[5]	15	2.0	0.13	3.2	.0057	C
6902	SB0/a:[1]	2781	2810	37.0(G52)	12.37	0.59[5]	27	14.5	0.54	6.6	.0057	
7679	SB0p[1]	5181	5154	71.1	13.14	0.54[1]	42	17	0.41	3.0	.0036	
						Confused Detection						
936	SB0$^+$[1]	1430	1465	18.2(G15)	11.21	0.95[5]	22	0.82	0.03	4.0	.0025	
941	Sb:[1]		NA	18.2(G15)	13.4:	0.55[5]	2.9					
						Undetected Galaxies						
750/1	E0-E0[3]	-	5128	70.5	12.71	0.94[1]	74	≤13	≤.18	-	.0037	
5813	E1[4]	-	1882	24.2(G50)	11.79	1.00[1]	19	≤1.8	≤.09	-	.0044	
5854	SB0$^+$[1]	-	1626	24.2(G50)	12.63	0.85[5]	8.9	≤1.6	≤.18	-	.0039	
6661	S0/a[1]	-	4316	60.6	13.11	0.88[1]	51	≤11	≤.21	-	.0041	
7252	S0p[1]	-	4733	64.4	12.91	0.63[5]	47	≤8.1	≤.17	-	.0027	
7377	S0$^+$[1]	-	3416	46.7	11.75	0.88[1]	67	≤6.0	≤.09	-	.0038	
7457	$S0_1$[3]	-	525	10.5	11.95	0.81[5]	3.3	≤0.29	≤.09	-	.0036	
7585	S0p[4]	-	3352	48.5	12.44	0.87[5]	42	≤7.5	≤.18	-	.0044	
7727	S0 /ap[2]	-	1846	26.1	11.36	0.89[1]	29	≤1.6	≤.05	-	.0032	

Notes to table 1:

Col. 2. Sources [1] de Vaucouleurs and de Vaucouleurs (1964), Reference Catalogue of Bright Galaxies.
[2] From 120-inch plate.
[3] Sandage (1961), Hubble Atlas of Galaxies.
[4] Sandage (1974), private communication.

Cols. 3 and 4. Km sec^{-1} (heliocentric).

Col. 5. Parentheses refer to group memberships given by de Vaucouleurs (1976), in Galaxies and the Universe, ed. A. Sandage and M. Sandage.

Col. 6. Except for NGC 936, corrected B(0) magnitudes from RCBG: m_{Holm} = B(0) - 0.30. m_{Holm} for NGC 936 from Holmberg (1958), Medd. Lunds Astr. Obs. Ser. 2, No. 136.

Col. 7. Based on B-V colors from sources [1] and [5], corrected for galactic reddening assuming E(B-V) = 0.033 csc $|b|$ Source [5] de Vaucouleurs, G., and de Vaucouleurs, A. 1972, Mem. R.A.S., 77, 1.

Col. 11. σ(M) = measurement uncertainty in M_{HI} (see text).

Col. 12. R.m.s. scatter in baseline after smoothing to 33 km sec^{-1}

Col. 13. (A) Previously detected by Lewis (1970), Observatory, 90, 264: $m_{HI} = 1.3 \times 10^9 M_\odot$
(B) Previously detected by Bottinelli et al. (1972), A.Ap., 21, 303: $m_{HI} = 2.5 \times 10^9 M_\odot$.
(C) Previously detected by Bottinelli et al. (1972): $m_{HI} = 1.6 \times 10^9 M_\odot$.
(D) See Haro (1956), Bol. Obs. Ton. y Tac., No. 14, 16.

cases $\sigma(T_A)$ is consistent with the system temperature and integration time. As in Paper I, we define the uncertainty in the hydrogen mass to be $\sigma(M) \equiv 0.8D^2\sigma(T_A)\Delta V \times 10^6\ M_\odot$ for the 140 foot telescope, where ΔV is the line width in km s^{-1}. For detected galaxies, we give the signal-to-noise ratio for the hydrogen mass, $M_{\mathrm{H\,I}}/\sigma(M)$. For the undetected galaxies, upper limits to $M_{\mathrm{H\,I}}$ are computed from $3\sigma(M)$, where ΔV is assumed to be 300 km s^{-1}.

In three cases, the telescope beam included other galaxies which might confuse the identification of the detected galaxy. In the case of NGC 936 this problem is severe, but for NGC 6340 and 7679 the possibility of confusion, while present, is probably small. Problems of confusion are elucidated below, where we discuss the galaxies individually. In these notes, "clean field" means that no other galaxies are found within 15′ of the program galaxy, δm_B is the approximate difference in B magnitudes between the program galaxy and the integrated light of the confusion galaxies, "NA" means not available; and RCBG and APG represent the *Reference Catalogue of Bright Galaxies* (de Vaucouleurs and de Vaucouleurs 1964) and the *Atlas of Peculiar Galaxies* (Arp 1966), respectively.

NGC 750/1.—Photo in APG (No. 166) shows bridge between 750/1 and very faint galaxy 2′ NW. Early-type companions 10′ distant. Not detected.

NGC 936.—NGC 941 (Sc) 13′ E; $\delta m_B \approx -2$; can equally well explain observed hydrogen if D (941) $\approx$ D(936). H I profile width $\sim$530 km s^{-1} centered at $\sim$1430 km s^{-1}.

NGC 1291.—Clean field, outer ring. H I line width abnormally narrow (50 km s^{-1}). Lewis (1970) derives same $V_{\mathrm{H\,I}}$ and $M_{\mathrm{H\,I}}$ in a 14′ beam.

NGC 1326.—Clean field, outer ring. Possible H I at V = 1014 km s^{-1} also. Detected by Balkowski *et al.* (1972), who report $M_{\mathrm{H\,I}} \approx$ 25 percent greater.

NGC 4670.—NGC 4673 (E1) 4′ SE; V(4673) $\approx$ 7000 km s^{-1}, so no confusion. APG (No. 163) photo shows prominent bulge in the nucleus and irregular outer structure. NGC 4670 = Haro No. 9 (Haro 1956); strong blue continuum and optical emission lines seen.

NGC 5813.—Clean field. Not detected.

NGC 5854.—Clean field. Type may be S0/a. Not detected.

NGC 6340.—IC 1251 and 1254 lie 6′ N and 8′ NE, respectively; $\delta m_B \approx -1.8$; V NA for either galaxy. If D (1251 + 1254) = D(6340) and all H I comes from these galaxies, then $M_{\mathrm{H\,I}}/L_{\mathrm{pg}} \geq 1$, an unreasonable value; thus confusion not likely. $(B - V)_0 = 1.07$ for IC 1254. Optical V(6340) measured by S. M. F. Previously detected by Balkowski *et al.* (1972), who report $M_{\mathrm{H\,I}} \approx$ 20 percent smaller.

NGC 6661.—NGC 6658 (S0/a) 10′ W, $\delta m_B \approx -0.8$, V(6658) = 4270. Not detected.

NGC 6902.—Clean field. RCBG notes faint outer ring and arms. $M_{\mathrm{H\,I}}/L_{\mathrm{pg}}$ is anomalously high and similar to Scd galaxies.

NGC 7252.—Clean field. Photo in APG (No. 226) shows outer streamers and a jet or plume. Possible spectral feature present below the detectable upper limit (see Fig. 1).

NGC 7377.—Clean field. Not detected.

NGC 7457.—Faint later-type galaxy 8′ NE; V(7457) NA. H I shows noisy bump at $\sim$900 km s^{-1} below 3 $\sigma(M)$ upper limit.

NGC 7585.—NGC 7576 (S0$^+$) 12′ SW; $\delta m_B \approx -2.2$; V(7576) = 3572. Photo in APG (No. 223) shows outer ring, but only northern half appears visible. Not detected.

NGC 7679.—NGC 7682 (Sb:) 5′ E; $\delta m_B \approx -0.85$; $(B - V)_0 \approx 0.97$ (RCBG); V(7682) NA. If D(7682) = D(7679) and all H I comes from 7682, then $M_{\mathrm{H\,I}}/L_{\mathrm{pg}}$ (7682) > 0.8, a very high value; thus confusion is not likely. Photo in APG (No. 216) shows both galaxies to be disrupted and probably interacting.

NGC 7727.—Clean field. Nearly face on. Photo in APG (No. 222) shows disrupted outer whorls. Not detected.

The value of $H\,\mathrm{I}/L \approx 0.5$ observed for NGC 6902 is truly remarkable for a normal galaxy of its type (SB0/a); values of H I/$L \approx 0.5$ are common for such later (Scd) galaxies, in which the H I is located predominantly in a disk. The values of H I/$L \approx$ 0.3–0.4 derived for the galaxies NGC 7679 and 4670 are also quite large but not anomalous in peculiar galaxies of this type (Paper I). NGC 6340 also shows a large value for H I/L, but field galaxies might contribute at least some of the H I observed in this case.

IV. RELATIONSHIPS BETWEEN H I CONTENT AND OTHER PROPERTIES

a) H I *Detectability and Apparent Magnitude*

Based on the data for morphologically normal S0s in Paper I and the present paper, the average apparent magnitude is 11.5 for detected galaxies and 11.4 for undetected galaxies. For bright S0s, then, apparent magnitude is not a reliable indicator of detectability at 21 cm. This lack of correlation results from the very large scatter in intrinsic gas fraction among S0s, which obscures the natural decline in signal strength to be expected with increasing faintness. Such a correlation presumably should set in when the observations are extended to fainter apparent magnitudes.

b) H I/*L and Color*

It is obvious from Table 1 that most of the bluer ($C_0' \leq 0.8$) galaxies in the program were detected, and that all but one of the program galaxies that were not detected are red. This suggests that the H I/L versus color correlation discussed in Paper I for galaxies later than S0 is valid for S0 galaxies as well. In order to show this, in Figure 2 we have plotted H I/L versus C_0' for the program galaxies and the other early-type galaxies listed in Tables 3 and 6 of Paper I (the present color index of NGC 3489 is based on photometry by Lasker 1970 transformed to $B - V$). Also shown are the regions in this plot where most Sb and Sc galaxies are found. The H I/L versus

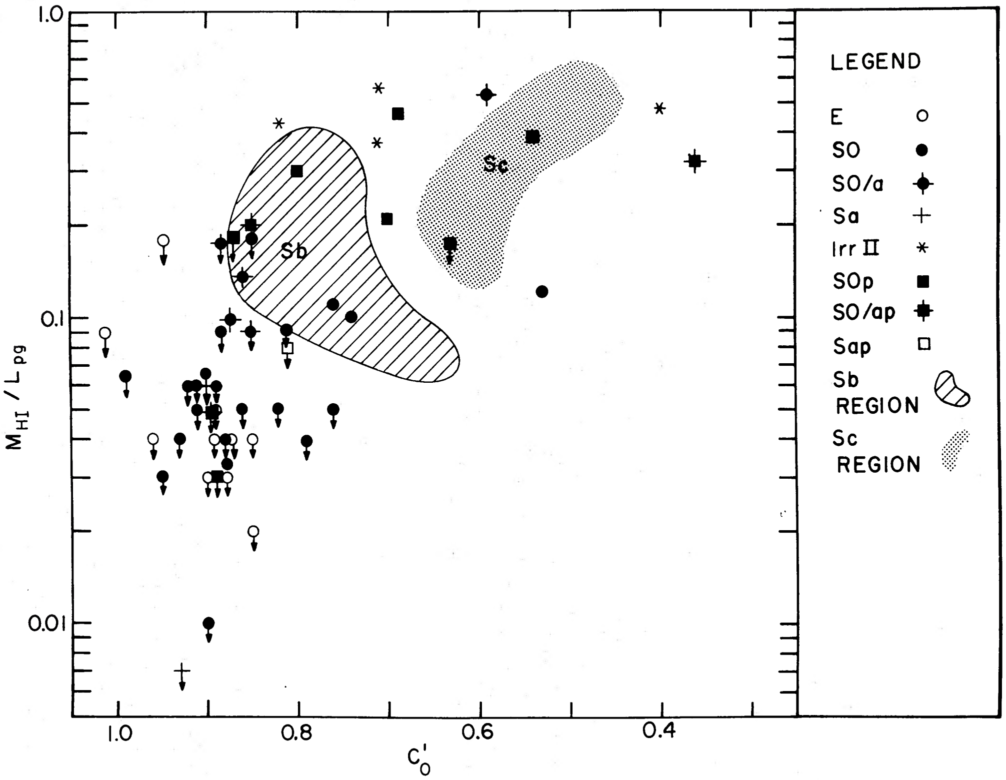

FIG. 2.—H I mass normalized to photographic luminosity versus color index for the program galaxies in this paper and for galaxies in Tables 3 and 6 of Paper I. Crosshatched and shaded areas represent regions of the plot heavily populated by Sb and Sc galaxies, respectively, and the approximate average values of $M_{\rm H\,I}/L_{\rm pg}$ and C_0' for these types of galaxies coincide with the symbols "Sb" and "Sc."

color relation holds up remarkably well, and it is clear that this same trend persists along the entire Hubble sequence and is valid for peculiar and Irr II galaxies as well. A very similar H I color relation has been found and discussed for dwarf galaxies by Bottinelli and Gouguenheim (1974).

c) H I/*L* and Cluster/Group Membership

No clear trends emerge from an inspection of Table 1 and Paper I regarding H I content and cluster membership. On the one hand none of the galaxies in the NGC 5846 group (all of which are red) were detected, yet many of the detected galaxies are group members (these detected group-associated galaxies are all predominantly blue in color). At our level of sensitivity, no S0 has been detected in a rich cluster such as the Virgo or Coma clusters, although several have been found in Fornax. A larger sample of detected S0 galaxies is required before possible effects of group membership on H I/*L* can be properly assessed.

d) Other Trends

No statistically significant correlation between $M_{\rm H\,I}$ and total galaxy luminosity is seen. As a group, the peculiar galaxies tend to be bluer and have larger amounts of H I than normal galaxies.

V. CONCLUSIONS

We have observed 17 highly selected early-type galaxies, mostly of type S0, and have detected 21 cm H I emission in seven of them. $M_{\rm H\,I}/L_{\rm pg}$ is generally correlated with the color of the galaxy, based on $B - V$ photometry, but some scatter is evident. Nearly all galaxies brighter than $m_{\rm Holm} \approx 13$ and with color indices $C_0' \leq 0.8$ were detected, whereas nearly all galaxies brighter than this apparent magnitude which were not detected are characterized by "red" color indices. In addition, H I is detected in the direction of two red galaxies, NGC 6340 and NGC 1291 (although the H I seen toward the former galaxy could conceivably be located in fainter, later galaxies also in the beam, and the latter galaxy is detected partly because of its nearness and partly because of its narrow line width).

The presence of H I is generally thought to be a necessary (but not sufficient) condition for the formation of stars, and blue optical colors are normally taken to signal the presence of young stars. Thus qualitatively speaking, the observed correlation of H I/*L* with color in the sense described above confirms this association between gas and recent star formation. NGC 1291 and 6340, as well as NGC 1023 (Paper I), appear to be examples of a class of galaxies in which a prominent interstellar medium is not associated with the formation of massive stars. As mentioned earlier, many questions arise concerning the source of the H I and how the H I might be stable against removal mechanisms. Such questions have been discussed in Paper II, and the additional data now available do not warrant a more detailed discussion at this time.

Further studies of these early-type galaxies would be of considerable interest, especially maps of the H I distribution made with high spatial resolution. Since we have tentatively suggested in Paper II that galactic winds (cf. Mathews and Baker 1971) can remove the gas from the spheroidal component of the stellar distribution in galaxies such as we observed, it would be of great interest to determine whether the H I is associated with the disk. In this regard it should be noted that all galaxies in which H I is detected show some evidence for an optically visible disk, and that except for the nearly face-on galaxy NGC 1291, the H I velocity profile shapes in the brightest S0 galaxies are reminiscent of the integrated H I profiles of disk-dominated later-type systems. On the other hand, scans of the 21 cm surface brightness in NGC 5102 by Balkowski *et al.* (1972) suggest that the hydrogen in this galaxy is concentrated toward the nucleus. This result is supported by preliminary evidence (Paper I) that star formation is most intense in the nucleus of NGC 5102 and declines with distance from the center. Therefore the evidence concerning the location of the gas in these systems is at present contradictory; perhaps the gas is distributed rather differently in different objects. Since the distribution and dynamics of the neutral hydrogen may well provide clues to the origin of the gas in S0s, maps of the gas having high spatial resolution would be extremely useful.

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BRUCE BALICK: Astronomy Department, University of Washington, Seattle, WA 98195

SANDRA M. FABER: Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064

JOHN S. GALLAGHER: School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455