THE ASTROPHYSICAL JOURNAL, 344:747–762, 1989 September 15

MOLECULAR GAS, THE INTERSTELLAR MEDIUM, AND STAR FORMATION IN S0 AND Sa GALAXIES

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Received 1988 December 9; accepted 1989 March 3

ABSTRACT

We present the results of a survey for CO $J = 1 \rightarrow 0$ emission from early-type disk galaxies—S0's, S0/a's, Sa's—in order to study their cool interstellar media and the global properties of their star formation. Of the 13 nearly normal S0's, we positively detected six and, marginally, a seventh. We also detected five, and possibly a sixth, of the seven S0/a or Sa galaxies in our sample. As have other investigators, we find a wide range of characteristics for the interstellar medium (ISM) in S0 and S0/a galaxies. There is a tendency for peculiar galaxies in our sample to have relatively stronger CO line strengths than do the more normal galaxies of about the same visual luminosity. We find average values for $L_{CO}/M(\text{H I})$ and the abundance of the far-infrared–emitting dust relative to the interstellar gas to be roughly similar to those derived for late-type spirals. We would expect neither if the interstellar media within the galaxies in our survey have exclusively an external source. Although some S0's have a total gas abundance that is comparable to that found for the spirals, typical fractional gas masses in these galaxies are about an order of magnitude less than those for Sb or Sc spirals. On average, the molecular masses for the early-type disk galaxies in our survey are comparable to those of the atomic gas, although there is wide variation in $M(H_2)/M(\text{H I})$ with weak evidence for variation in the ratio with Hubble type. We therefore conclude that morphological type is not the sole factor in determining the global molecular-to-atomic gas mass ratio. We repeat our warnings about the interpretation of the far-infrared emission from these galaxies and adopt observations of the visual emission lines as the best tool for studying massive star formation. For the four galaxies in our survey for which such data exist, the rate of star formation is about an order of magnitude less than that in late-type spirals of the same visual luminosity. The efficiency of star formation, however, is similar in this small sample of galaxies. We conclude, therefore, that spiral structure is largely irrelevant to the global rate and efficiency of star formation in galaxies. X-radiation has been detected from some of the objects in our sample. If this emission arises from extended hot gas rather than from discrete sources, we derive a cooling rate for the gas that is comparable to the rate of replenishment due to mass loss from evolved stars. Both rates, however, are considerably below the estimated star formation rate, which indicates that the present-day ISM was not created entirely by material lost by dying stars. For most of the galaxies in our survey, we conclude that the ISM is largely a remnant from earlier epochs of star formation, enriched by evolved stars.

Subject headings: galaxies: interstellar matter — interstellar: molecules — stars: formation

I. INTRODUCTION

The morphology of galaxies may play a critical role in the structure and evolution of the interstellar medium (ISM) and in the large-scale processes of star formation. For this reason, we have expanded our studies of spiral, irregular, and dwarf galaxies (e.g., Young *et al.* 1986; Thronson and Bally 1987*b*; Tacconi and Young 1987; Kenney 1987; Young *et al.* 1989; Thronson and Bally 1989) to include early-type disk galaxies without spiral structure, the S0 (lenticular) galaxies, on which we report here. These systems are often taken to be "transition" objects, in some sense, between ellipticals and spirals. True members of this class have a large bulge, a distinct disk, and no spiral structure. The role of spiral arms, for example, or the effects of a very low mass ISM in the creation of stars or the structure of the ISM in galaxies can be studied using S0 galaxies and their relatives as contrasts to the spirals.

Star formation on a large scale may be taking place in an environment in lenticulars that is very different from that in more gas-rich spirals. The importance of this can be demonstrated by considering a pair of key factors in the global gas-star cycle in galaxies, the star formation rate ($\dot{M}_{SF}$) and the mass return rate from evolved stars ($\dot{M}_{rtn}$), as a function of galaxy morphological type. In late-type disk galaxies (irregulars and spirals) star formation proceeds in gas-rich environments, and $\dot{M}_{SF} \gg \dot{M}_{rtn}$. In this case, the rate, efficiency, and location of stellar birth may be governed by the large-scale dynamics of the gas. At the other end of the Hubble sequence, elliptical galaxies may have returned very large amounts of processed material to their ISMs over time, but the rate is low and the gas that is present is extremely hot (e.g., Nulsen, Stewart, and Fabian 1984; Fabbiano 1986). For that reason, there is little star formation taking place in normal members of this class, and it may be that $\dot{M}_{SF} \ll \dot{M}_{rtn}$. In between these two extremes, the S0 galaxies have star formation rates calculated to be in the range 0.1–1 $M_\odot$ yr^{-1} (Pogge and Eskridge 1987; Thronson and Bally 1987*a*; Hunter *et al.* 1989), a rate that is comparable to the mass return rate derived by Faber and Gallagher (1976), $\dot{M}_{rtn}$ ($M_\odot$ yr^{-1}) $\sim 10^{-10} L_B$ ($L_\odot$), with $L_B \approx 10^9$ $L_\odot$ for the more luminous members of this class (see § II*b* for our definition of blue luminosity). Thus, the rate and location of star formation in many S0's may be closely coupled to the

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rate and location of mass return: star formation in lenticulars may be related directly to the old stellar population. Moreover, since there is an approximate equality calculated between the rates of star formation and mass return, slight variations between galaxies—distribution of stellar mass, modest amounts of external gas infall or residual nonprocessed gas, different stellar mass functions, galaxy mergers—can be expected to alter significantly those observational characteristics that depend upon star formation. That is, one can *a priori* expect wide variations in nonnuclear emission-line strengths, radio and far-infrared continuum emission, visual appearance, and the mass of the cool interstellar medium in S0 galaxies. This conjecture appears to be supported (e.g., Sandage 1961; Bothun 1982; Sandage 1986; Balkowski, Alloin, and Le Denmat 1986; Wardle and Knapp 1986; Thronson and Bally 1987*a*; van Driel 1987; Wrobel and Heeschen 1988; Thronson, Bally, and Hacking 1989; Bally and Thronson 1989; Walsh and Knapp 1989; Walsh *et al.* 1989). However, until a few years ago many workers concluded that almost all of the primordial gas was consumed in the first burst of star formation and that any subsequent stellar creation can easily keep up with the mass return rate, so little or no cool gas should remain in normal S0's, except in the event of injection from an external source.

One major result from the studies of external galaxies over the last decade has been the discovery of gas in "gas-free" S0's and star formation in what were throught to be inert galaxies. With improvements in telescope sensitivity, H I has been detected in increasing numbers of lenticulars (see the compilation of Wardle and Knapp 1986). More significantly, millimeter-wave carbon monoxide, indicative of the presence of molecular gas, has been reported from a number of S0's (e.g., Thronson 1988; Sage and Wrobel 1989, Wiklind and Henkel 1989). Observers at visual and ultraviolet wavelengths have begun to study the composite spectra of this type of galaxy. In a number of cases, ongoing or relatively recent star formation was the most straightforward explanation for their blue stellar population (Gunn, Stryker, and Tinsley 1981; Rose 1985; Balkowski, Alloin, and Le Denmat 1986; O'Connell 1986*a*; Rocca-Volmerange and Guideroni 1987; Kjaergaard 1987; Bertola *et al.* 1987; Gregg 1989). Nonnuclear ionized gas has now been detected in a relatively large number of S0 and related galaxies by, for example, Phillips *et al.* (1986), Pogge and Eskridge (1987), Hunter *et al.* (1989), and Kim (1989), although visual-line emission from these objects has been known for over half a century (Mayall 1939).

With the extensive *Infrared Astronomical Satellite* (*IRAS*) data base, studies of early-type galaxies have become a popular topic in the literature on the infrared emission from galaxies. Jura (1986) and Jura *et al.* (1987) first showed that a number of elliptical and S0 galaxies can easily be found in the *IRAS* survey data, which indicated that these objects were not as inert as had been widely believed. Shortly thereafter, Thronson and Bally (1987*a*) presented a short study of the mid- and far-infrared spectra of these objects, warning about casual interpretation of their emission. More recent studies, including those of Dressel (1988) and Wrobel and Heeschen (1988), concentrated on determining whether or not star formation was the ultimate source of the infrared emission. Finally, more extensive searches through the *IRAS* data base have revealed large numbers of lenticular galaxies that show emission from warm dust (Knapp *et al.* 1989; Bally and Thronson 1989; Walsh *et al.* 1989; Thronson, Bally, and Hacking 1989; Walsh and Knapp 1989). The detection of warm dust emission was not entirely unexpected by many researchers, since the major subtypes in S0 classification are distinguished by the presence or absence of dust.

Although it is hardly *outré* any longer to consider S0 galaxies possessing significant interstellar media, there is considerable controversy as to the relation between the dust, atomic gas, and the presence of star-forming material. Our survey for CO line emission from these galaxies was motivated to determine whether or not molecular gas, the fuel for stellar creation, was common in galaxies with a low rate of star formation. In addition, we are interested in the processes that govern star formation in low–gas-mass environments or in galaxies devoid of the spiral structure that has attracted the attention of the majority of astronomers. Finally, we also were interested in comparing the total mass of the interstellar medium in these systems with that expected to accumulate over a Hubble time of mass loss by evolved stars.

II. THE OBSERVATIONS

a) The Telescopes

All but one of the early-type disk galaxies reported on here were observed using the 13.7 m radome-enclosed Cassegrain telescope of the Five College Radio Astronomy Observatory.[5] The detector system is a cooled Schottky diode mixer operating at 115.271203 GHz, the rest frequency of the $J = 1 \rightarrow 0$ transition of $^{12}C^{16}O$ (hereafter, CO) that we observed in this program. At this frequency, the half-power beamwidth of the telescope is measured to be 45″. Reference positions were typically only a few arcminutes away from the galaxy, in regions assumed to be devoid of contaminating CO emission. The galaxies were observed during three observing runs, in 1986 November, 1987 March, and 1988 April.

Absolute calibration was obtained by regularly observing standard sources, usually Ori A and IRC +10216, and relative calibration used the standard ambient-temperature chopper-wheel method. We estimate the total systematic uncertainty in our observations to be about $\pm 20\%$ ($1\ \sigma$ rms). Details about extragalactic observations with the FCRAO telescope may be found in the recent papers by Kenney (1987), Kenney and Young (1988*a*), and Young *et al.* (1986).

The same techniques of observations and reduction were used with our observation of the CO emission from NGC 404, obtained using the NRAO 12 m telescope on Kitt Peak, Arizona.[6]

Our results and additional information about the objects in our program are presented in Table 1, where column (1) lists the names of the objects; column (2) is the size of the galaxy from the UGC and the galaxy's blue magnitude, taken from either Sandage and Tammann (1981), the UGC, or the reference for the 21 cm H I observations; column (3) is the total 21 cm H I line flux for each object, taken from the literature; column (4) lists the total 60 and 100 μm flux densities, uncorrected for color effects, determined from the *IRAS* data base using "line-add" programs and the 1986 February calibration; column (5) is the total CO line strength; column (6) is the

[5] The Five College Radio Astronomy Observatory is operated with support from the National Science Foundation under grant AST 85-12903 and with permission of the Metropolitan District Commission of the Commonwealth of Massachusetts [Michael Dukakis, Governor].

[6] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

OBSERVED PARAMETERS

Name (1)	UGC Size (arcmin) B_T^0 (2)	H I Flux (Jy km s^{-1}) (3)	F_{60} F_{100} (Jy) (4)	I_{CO} (center) (rebers) (5)	V_{LSR} Δv (km s^{-1}) (6)	f_{center} (7)	CO Flux (Jy km s^{-1}) (8)
NGC 404 (UGC 718)	3.6 × 2.4 10.96	49.0[a]	2.26 5.6:	1.7 ± 0.35	−58 100	0.48	148 ± 30
NGC 693 (UGC 1304)	3.2 × 1.6 13.5	9.3[b]	7.3 12.2	≤0.5	1570 600	0.59	≤35
NGC 1819 (UGC 3265)	1.7 × 1.2 13.7	2.8[c]	7.0 11.4	3.9 ± 1.0	4430 400	0.71	229 ± 40
NGC 2273 (UGC 3546)	2.9 × 1.7 11.73	8.8[d]	6.8 12.4	1.7 ± 0.35	1950 250	0.57	120 ± 25
NGC 2685 (UGC 4666)	5.5 × 3.5 11.86	32.3[e]	0.35 1.8	≤0.7	880 300	0.33	≤90
NGC 3032 (UGC 5292)	2.0 × 1.7 12.55	1.6[f]	1.7 4.0	1.3 ± 0.3	1570 180	0.64	85 ± 25
NGC 3226 (UGC 5617)	2.5 × 2.2 12.3	...	7.5 15.3	≤0.6	1350 300	0.58	≤43
NGC 3413 (UGC 5960)	1.9 × 0.8 13.1	10.3[g]	1.0 1.9	≤2	620 400	0.75	≤111
NGC 3593 (UGC 6272)	5.2 × 2.1 10.78	8.1[b]	19.0 35.0	10.2 ± 2.0 (extended)	580 300	0.92	876 ± 160
NGC 3611 (UGC 6305)	2.7 × 2.7 12.28	8.9[b]	5.0 7.9	≤3	1620 400?	0.52	≤240
NGC 4138 (UGC 7139)	4.7 × 2.5 11.45	...	... ...	0.9 ± 0.3	1050 300	0.37	100 ± 33
NGC 4383 (UGC 7507)	1.8 × 0.9 12.98	23.8[b] 44[h]	8.5 12.0	1.6 ± 0.5	1675 350	0.74	90 ± 35
NGC 4457 (UGC 7609)	3.4 × 2.8 11.12	3.3[b]	4.7 9.4	4.7 ± 1.0	850 300	0.44	493 ± 120
NGC 4459 (UGC 7614)	3.5 × 2.7 11.49	<0.07[i]	1.7 4.2	1.3 ± 0.6	1050 200	0.45	120 ± 55
NGC 4526 (UGC 7718)	7.0 × 2.7 10.59	<0.18[i]	5.8 15.5	≤2	375? 400	0.38	≤220
NGC 4710 (UGC 7980)	4.3 × 1.3 11.85	≤0.29[i]	6.0 14.3	4.3 ± 1.0 (extended)	1110	2.10	200 ± 30
NGC 4753 (UGC 8009)	4.5 × 2.5 10.85	...	2.6 8.0	≤1	1200 400	0.40	≤104
NGC 5363 (UGC 8847)	6.0 × 6.0 11.06	1.80[j]	1.9 6.2	≤1.4	1150 600	0.26	≤220
NGC 5866 (UGC 9723)	6.5 × 3.0 10.86	<9.0[k]	5.1 16.5	2.3 ± 0.5 (extended)	800 400	0.89	240 ± 80
NGC 7013 (UGC 11670)	5.2 × 1.6 11.60	21.6[l] 15.5[m]	1.9 6.5	1.3 ± 0.6	750 300	0.43	126 ± 63
NGC 7465 (UGC 12317)	1.2 × 0.7 13.3	11-28?[n]	3.1 6.6	2.2 ± 0.4	1950 250	0.82	119 ± 30
NGC 7625 (UGC 12529)	1.5 × 1.5 12.49	18.3[o] 11.2[b]	9.0 18.3	5.7 ± 1.0	1630 290	0.69	344 ± 70

[a] Baars and Wendker 1976.
[b] Giovanardi, Krumm, and Salpeter 1983.
[c] Sulentic and Arp 1983.
[d] Gallagher, Faber, and Balick 1975.
[e] Bieging 1978.
[f] Bieging and Bierman 1977.
[g] Chamaraux, Balkowski, and Fontanelli 1987.
[h] Helou, Hoffman, and Salpeter 1984.
[i] Kenney and Young 1989.
[j] Thuan and Wadiak 1982.
[k] Balkowski and Chamaraux 1983.
[l] Knapp *et al.* 1984.
[m] Burstein, Krumm, and Salpeter 1987.
[n] Huchtmeier *et al.* 1983.
[o] Knapp, Kerr, and Williams 1978.

observed or expected LSR velocity of the CO line and the width of the spectrum over which we integrated to obtain the line strength; column (7) gives our estimate of the fraction of the CO emission from the galaxy that is included in our beam (discussed below); and column (8) is our estimate of the total CO line flux estimated to come from each object. Spectra of the objects are shown in Figure 1, with the exception of that for NGC 404, which will be discussed elsewhere in more detail (Thronson and Hunter 1989), and NGC 4710, which is included in Kenney and Young (1988*a*). The uncertainties quoted for the CO line fluxes are quadratic sums of all the sources of error: baseline uncertainties, internal (statistical)

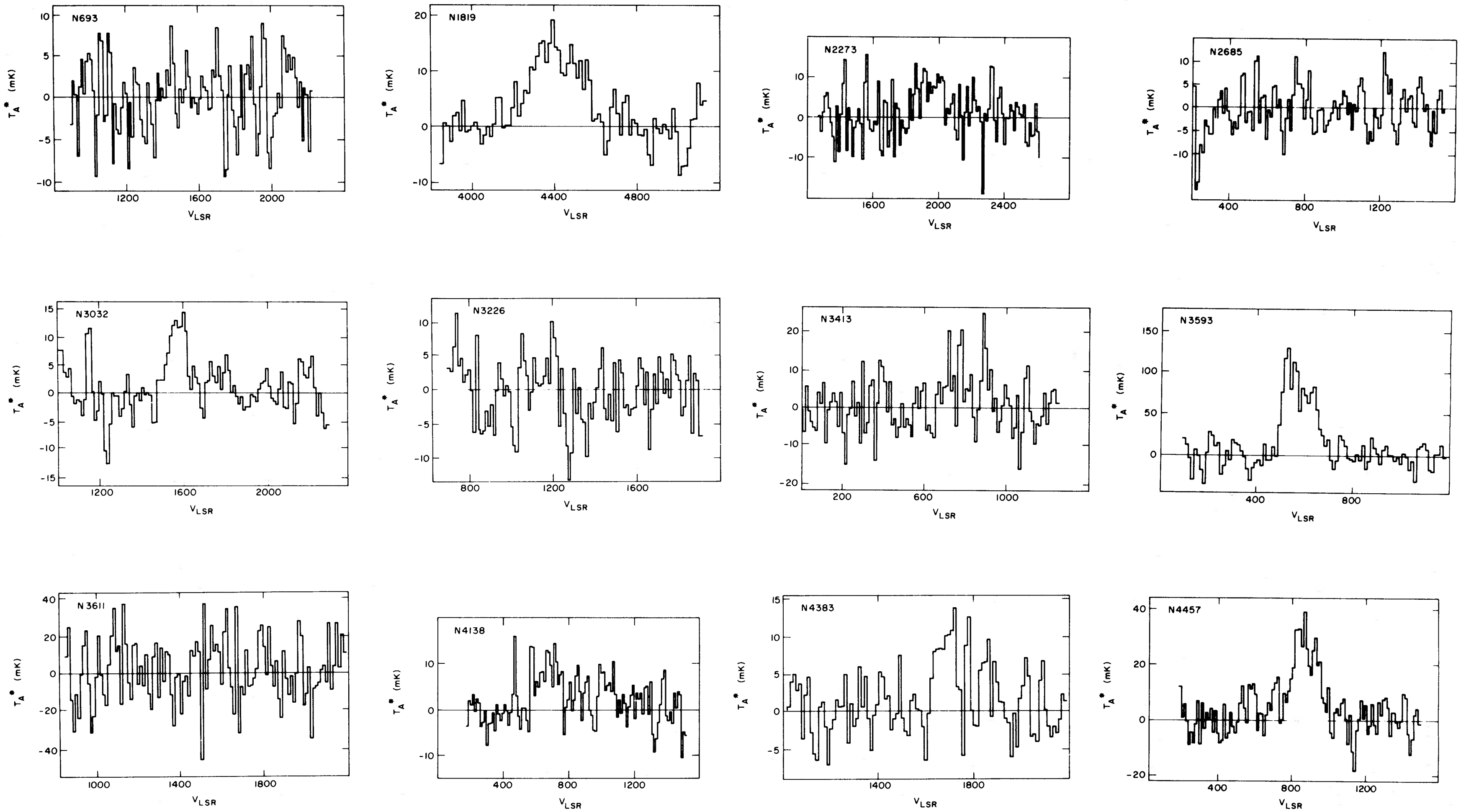

FIG. 1.—CO spectra for the early-type disk galaxies in our program, with the exception of NGC 404 (Thronson and Hunter 1989) and NGC 4710 (Kenney and Young 1988*a*). In all cases, the raw data were smoothed with a Hanning function with a width of 15 km s^{-1}. The intensities are given in units of mK and are T_A^*.

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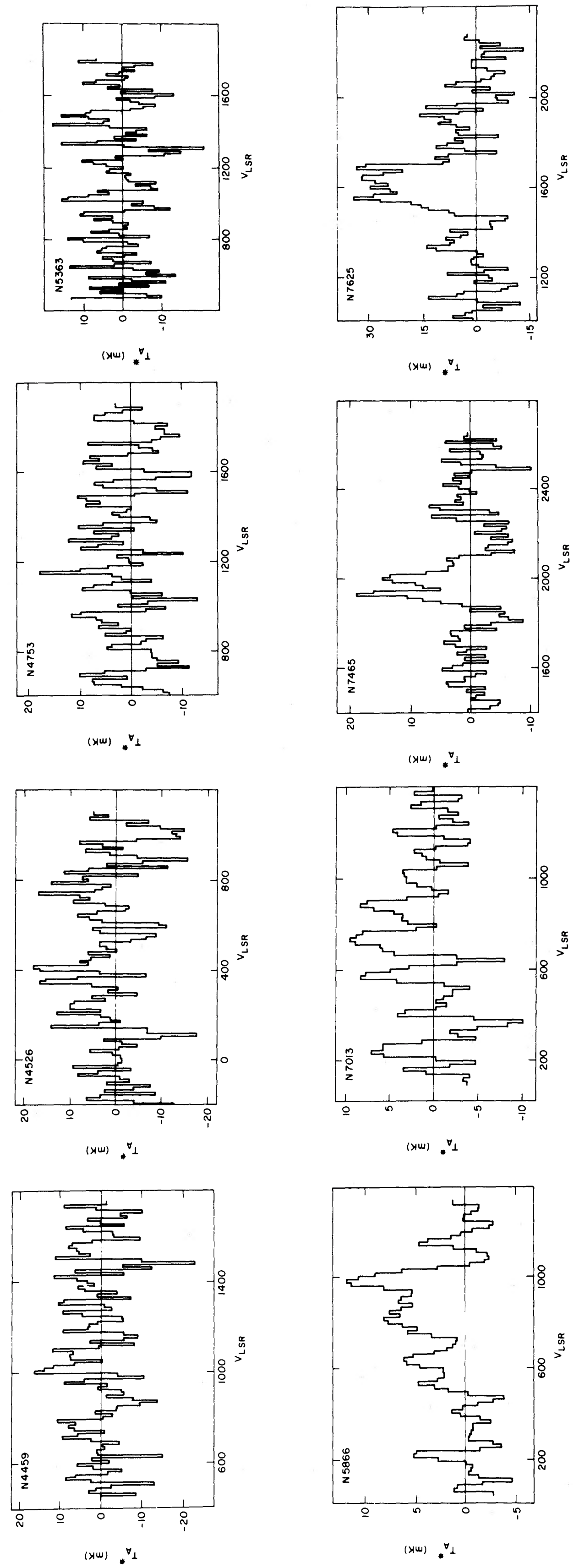

FIG. 1.—*Continued*

errors, plus a 20% calibration uncertainty. We note that there are often significant differences in the visual magnitudes quoted for galaxies, and we estimate variations of about 1 $\sigma = 0.2$ magnitudes. Taking into account beam size, efficiency, and calibration differences, the agreement between our observations and the survey by Sage and Wrobel (1989) is fair. The outstanding difference between the observations is our nondetection of NGC 4459, which we carefully reobserved. We have no explanation for the difference.

b) Measured and Derived Quantities

Distances to the galaxies were usually determined using the observed radial velocity of the H I or CO line and a Hubble constant of 75 km s^{-1} Mpc^{-1}. The exceptions were systems such as NGC 404 that are too close to be participating in the Hubble flow or galaxies in the Virgo Cluster for which we adopted a distance to all objects of 20 Mpc, which is a common value in the literature. Wherever necessary we have corrected derived quantities taken from the literature to the distances that we adopt.

The CO line strength for each galaxy is given in rebers (1 Rb $\equiv$ 1 K km s^{-1}) and is the integrated peak antenna temperature,

$$I_{\rm CO}({\rm Rb}) = \int T_A^*({\rm K}) dv ({\rm km\ s^{-1}}) ,$$

within the 45″ FCRAO telescope beam or the 55″ NRAO beam centered on the visual nucleus of each object. Only internal uncertainties are quoted for each observation, and we list as detections only those with a signal-to-noise ratio in excess of about 3. The LSR velocities were estimated from the spectra and are uncertain by about ± 50 km s^{-1}. The regions over which we integrated to obtain the line strength were determined from the CO observations, if possible, or else the H I data. The width of this region, Δv, is slightly (about 50 km s^{-1}) wider than our estimate of the full width of the CO or H I line. We consider NGC 7013 to be a tentative detection for, although its formal signal-to-noise ratio is less than 3 because of a bad baseline, there is a prominent feature in the CO spectrum which agrees in velocity and width with the H I line.

In our survey, we have little information about the distribution of CO emission within the galaxies, a major systematic uncertainty that will haunt all our analyses. We have derived estimates of the total CO fluxes by making corrections for source-beam coupling. The total CO flux has been estimated using the relation.

$$S_{\rm CO}({\rm Jy\ km\ s^{-1}}) = C_{\rm PS} \int T_A^*\, dv / f({\rm Rb}) , \quad (1)$$

where $S_{\rm CO}$ is the total line flux, $C_{\rm PS}$ is the point-source calibration factor (41.7 Jy K^{-1} for the FCRAO telescope), and f is the correction factor for source-beam coupling. The value for f is derived via

$$f = \frac{\int T_R(\Omega) B(\Omega) d\Omega}{\int T_R(\Omega) d\Omega} , \quad (2)$$

where $T_R(\Omega)$ is the brightest temperature distribution of the galaxy or a hypothetical model and $B(\Omega)$ is the telescope beam pattern, normalized to unity at beam center and assumed to be Gaussian. For a point source f is equal to unity, but for an extended source f is less than unity.

In order to estimate the coupling correction factor, we have used a Gaussian beam with a half-power beamwidth of 45″ (or 55″ for the NRAO telescope in our observation of NGC 404), and assumed an intrinsic CO brightness distribution. The major uncertainty in the CO fluxes is therefore the coupling correction factor, since we have not measured the true distribution of the molecular emission in most of our galaxies. We have assumed that the distributions are azimuthally symmetric exponentials with scale lengths equal to $0.1D_{25}$, since this form is found to represent the CO distribution adequately in a handful of early-type Virgo spirals (Kenney and Young 1988*a*). For NGC 3593, NGC 4710, and NGC 5866 we observed exponential scale lengths of 0′.3, 0′.1, and 0′.65, respectively. Two of these values are in good agreement with the scale length estimated from the visual data of $0.1D_{25}$ = 0′.5, 0′.4, and 0′.6, respectively, that we would have assumed had we not mapped these objects. The difference between observed and assumed size distributions for the CO emission in these galaxies indicates that our estimates for the total CO flux from the objects are uncertain by about a factor of 2. For the three galaxies that were mapped, the flux in column (8) of Table 1 is the *measured* total line flux. Based on the extensive H I mapping that exists for many S0 galaxies and shows a complicated distribution of the atomic gas (e.g., van Driel 1987), we emphasize the uncertainty in our approximation to the true molecular gas distribution.

c) The Galaxies

The primary goal of our program was to detect CO emission, a putative tracer of H_2 mass, from a number of S0 and Sa galaxies and to determine the nature of their interstellar media and the characteristics of large-scale stellar birth. Our observing list was compiled from a number of sources in the literature, primarily H I and infrared surveys of early-type galaxies. Table 2 is an abridged compilation of information on these objects. We primarily searched galaxies that were strong sources of 21 cm H I or far-infrared emission, and it is likely that our source list is strongly biased toward early-type disk galaxies with at least *some* interstellar medium.

Significant confusion exists in the morphological classification of individual S0, S0/a, and Sa galaxies, although they are three distinct, well-defined types of objects. Even relatively nearby galaxies appear different to individual astronomers, which is reflected directly in the range of classifications that are assigned. Table 2 includes the variety of classifications that we were able to find in standard references. We judge the correct classification to be the majority choice from the variety of sources in the literature. Although the assumption is questionable, we take S0/a and Sa galaxies to be closely related objects, since we are most interested in contrasting the true lenticulars with other disk galaxies. Based on our summary in Table 2, we conclude that NGC 404, 693, 1819 (barred), 2685 (peculiar), 3032, 3413, 4138, 4459, 4526, 4710, 5363, 5866, and 7465 are S0 galaxies. We also assume that NGC 2273, 3593, 3611, 4383, 4457, 7013, and 7625 are Sa's or S0/a's. NGC 3226 is an elliptical, and NGC 4753 is too peculiar or too uncertain to classify; we did not detect CO emission from either. Of the S0's, we positively detected (S/N $\geq$ 3) six of the 13 that we observed, with a possible seventh detection. We observed seven Sa galaxies and positively detected five, with a possible sixth detection.

We can compare a variety of observational quantities for the galaxies in our program with those derived for larger samples of S0 and Sa galaxies, as an estimate of how representative our objects are. In Figure 2 we present a histogram of the blue

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TABLE 2

S0 GALAXIES: MORPHOLOGY AND ENVIRONMENT

Name	RC2 Type[a]	RSA Type[b]	UGC Type	V_{opt}	Comment on Environment	Comment on Morphology
NGC 404 (UGC 718)	SA(s)0$^-$:	S0$_3$(0)	E–S0	−35		circular dust lane
NGC 693 (UGC 1304)	S0	...	S	1550	In triple chain N676–693–706; companions at 20′, 50′ (UCG)	
NGC 1819 (UGC 3265)	...	...	SB0	4440	Projected location near center of cluster 0510.0+0458 (brighest in cluster?)	
NGC 2273 (UGC 3546)	SAB(rs)0/a:	...	SBa	1950		Markarian galaxy
NGC 2685 (UGC 4666)	(R)SB0	S0$_3$(7)pec	pec	868		The Spindle; Arp 336; appears cigar-shaped with equatorial rings (UGC); X-ray source
NGC 3032 (UGC 5292)	SAB(r)0	S0$_3$(2)/Sa	S0	1568		Internal absorption ring; nearly face-on (Hubble Atlas)
NGC 3226 (UGC 5617)	E2:pec	...	E	1338	Contact pair with NGC 3227; VV 209b, Arp 94; in N3189–3190 group; "comp. on edge of faint loop ext. opp. galaxy" (Arp)	
NGC 3413 (UGC 5960)	S0, sp	...	Sa?		N3395 group	
NGC 3593 (UGC 6272)	SA(s)0/a:	Sa pec	S0	549	Leo group	X-ray source
NGC 3611 (UGC 6305)	SA(s)a, pec	Sa	Sa	1754	Pair with U6306; disturbed? N3640 group (UGC)	"Smooth very faint disk with spiral arc or ring fragment in direction towards U6306" (UGC)
NGC 4138 (UGC 7139)	SA(r)0	Sab(r)	S0	1039		Ring of H II regions 30″ × 50″ (Pogge and Eskridge 1987); 2 H I rings; inner one coincident with H II
NGC 4383 (UGC 7507)	Sa:pec	S0:	pec	1700	In Virgo Cluster; pair with U7504 2′.6 away (UGC)	Markarian galaxy; interacting pair
NGC 4457 (UGC 7609)	RSAB(s)0/a	Rsb(rs)II	S0/Sba	738	In Virgo Cluster (southern extension)	Spiral arms readily apparent in Hubble Atlas photo
NGC 4459 (UGC 7614)	SA(r)0$^+$	S0$_3$(3)	S0	1111	In Virgo Clister; companion 2′.2 away (UGC)	Prominent internal absorption nearly face-on (Hubble Atlas); X-ray source
NGC 4526 (UGC 7718)	SAB(s)0$^+$	S0$_3$(6)	S0	487	In Virgo Cluster	Internal dust ring (with H II region?) $i \sim 70°$ (Hubble Atlas)
NGC 4710 (UGC 7980)	SA(r)0$^+$:sp	S0$_3$(9)	S0-a	1117	In Virgo Cluster	Prominent absorption; nearly edge-on (Hubble Atlas)
NGC 4753 (UGC 8009)	I0	S0 pec	...	847	3–4 other galaxies with same magnitude, velocity 200 km s^{-1}, within 1°; cluster?	Broad irregular absorption lanes; X-ray source
NGC 5363 (UGC 8847)	I0	S0$_3$(5)	?	1125	Pair with UGC 8853 (an Sbc 14′ away)	
NGC 5866 (UGC 9723)	SA0+Sp	S0$_3$(8)	S0	788	Member of group with N5907 and N5879	Edge-on, prominent dust lane tilted by 2° with respect to halo/bulge (Hubble Atlas); X-ray source
NGC 7013 (UGC 11670)	SA(r)0/a	...	Sa	570	Well isolated on Zwicky charts	Hα emission detected (Pogge and Eskridge 1987)
NGC 7465 (UCG 12317)	PSB(s)0+:	...	SB0	1994	N7448 group, brightest in subgroup of 3 (UGC)	Markarian 313
NGC 7625 (UGC 12529)	SA(rs)a, pec	S pec	...	1784	VV 280, Arp 212, III Zw 102	"Narrow chaotic absorption tubes across one end" (Arp); interacting pair

[a] De Vaucouleurs, de Vaucouleurs, and Corwin 1976.
[b] Sandage and Tammann 1981.

luminosities for the galaxies that we surveyed for which data are available.[7] Also included are the same data for the survey of primarily spiral galaxies by Young *et al.* (1989). Comparison with the Young *et al.* survey is appropriate, since the CO data were obtained with the same instruments as our survey of S0's and Sa's, and the data reduction was similar. The objects included in our survey are indicated by boxes enclosing their NGC numbers in Figure 2. The S0 galaxies appear to have a maximum near $L_B = 10^9\ L_\odot$, close to the maxima for both field and Virgo Cluster S0's in the luminosity function of Binggeli, Sandage, and Tammann (1988), which also shows that there are very few S0's with L_B greater than about $10^{10}\ L_\odot$ or

[7] Beware: we define L_B as the radiation within the B passband, which is *not* a standard convention. In this system, for example, the blue luminosity of the Sun is 0.14 $L_\odot$, where 1 $L_\odot \equiv 3.85 \times 10^{33}$ ergs s^{-1}. Blue luminosities taken from the literature have been converted to this system where necessary.

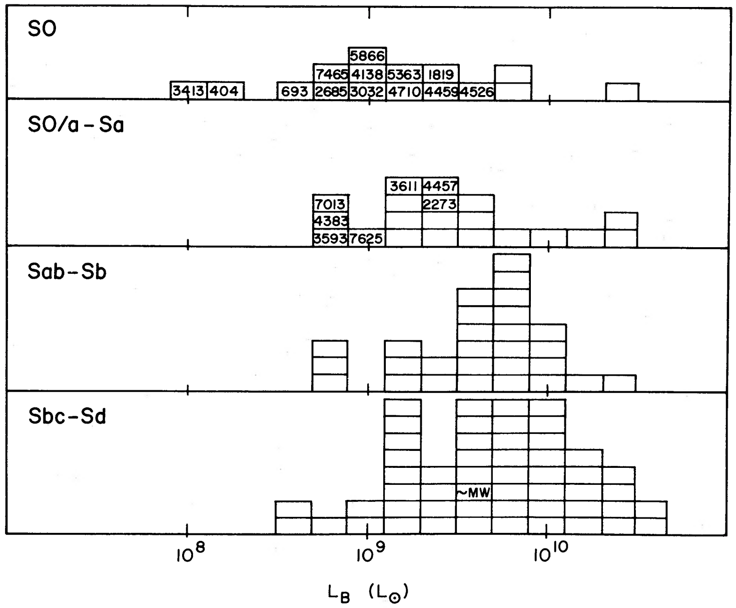

FIG. 2.—Distribution of blue luminosities for the early-type disk galaxies in our study and the spirals studied by Young *et al.* (1989). Please note our definition of L_B in § II*b*. Galaxies from our study are indicated by NGC numbers within the boxes. Because of the higher stellar mass-to-light ratio for the earlier type galaxies, the derived median galaxian masses are almost the same for the four morphological types in the figure. The approximate location of the Milky Way is indicated by "~MW."

less than about 10^8 $L_\odot$. The distribution of our small sample looks similar. Compared with the Binggeli, Sandage, and Tammann luminosity function, Young *et al.* studied the visually luminous late-type spirals. We therefore are able to extend the relations studied by Young *et al.* and Verter (1987, 1988) between many global quantities to lower luminosities and more typical galaxies. However, the primary contribution of this CO survey is to include galaxies with morphological types that are substantially different from those studied to date.

Our data on blue luminosities can be made more useful with a stellar mass-to-luminosity ratio. There is a large amount of uncertainty in these values for galaxies, but we adopt average values of $M_*/L_B = 50$ (Sbc–Sc), 80 (Sab–Sb), 110 (S0/a–Sa), and 120 (S0) from the work of Lauer (1985), van Albada *et al.* (1985), van der Kruit and Freeman (1986), Mathews (1988), and references therein. Based on the range of values in the literature, these ratios are uncertain by about a factor of 2 for any individual object, but are probably within about 30% for a given morphological class. Figure 2 then demonstrates that the lenticulars in our study have close to the same stellar mass as the giant spirals studied by Kenney (1987), Kenney and Young (1988*a*), and Young *et al.* (1989): both have median masses of $M_* \approx 2 \times 10^{11}$ $M_\odot$. For comparison with some of our derived quantities discussed below, for the Milky Way, $M(\text{H I}) = 2.4 \times 10^9$ $M_\odot$ and $M(H_2) = 2.2 \times 10^9$ $M_\odot$ (see the compilation of Sanders and Scoville 1988). The stellar mass and blue luminosity of the Milky Way are about 2.6×10^{11} $M_\odot$ and 3.8×10^9 $L_\odot$, respectively (Hodge 1985).

d) Data Analysis and Even More Caveats

The major observational goal of this program was to determine the amount of molecular material within early-type disk galaxies. Our observations demonstrate that at least some H_2 exists in these objects, but we must adopt a conversion from integrated CO line strength to $M(H_2)$. We shall adopt

$$M(H_2)(M_\odot) = 1.1 \times 10^4 D^2(\text{Mpc}) S_{\text{CO}}(\text{Jy km s}^{-1}) , \quad (3)$$

which is based on

$$N(H_2)(\text{cm}^{-2}) = 2.8 \times 10^{20} \int T_R \, dv(\text{Rb}) . \quad (4)$$

Approximately this relationship has been used for over a decade (e.g., Schneps *et al.* 1978), while this particular equation is derived by Kenney and Young (1989) and is distilled from the study of Milky Way molecular clouds by Scoville *et al.* (1987) and Bloemen *et al.* (1986). The coefficient is within a factor of 2 of that derived or adopted in other studies of giant spirals (e.g., Liszt 1982; Young and Scoville 1982; Kutner and Leung 1985; Knapp, Helou, and Stark 1987; Dickman, Snell, and Schlerb 1986). From this previous work, it is likely that our adopted conversions are applicable to giant spiral galaxies, and we assume that they also apply to the luminous nonspiral S0's. Probably the most complete discussion of wide application of a universal factor between $M(H_2)$ and CO line flux has been presented in Maloney (1987) and Maloney and Black (1988; see also van Dishoeck and Black 1988). These authors emphasize the effects of lower metallicity and higher ultraviolet flux on the carbon monoxide in molecular clouds: both effects can significantly lower the CO emission more than the H_2 mass, which would increase the coefficients in our equations (2) and (3), We expect, however, that this is not a serious problem with the lenticulars, since these are galaxies with, on average, heavy-element abundances similar to those of spirals with the same visual luminosity (Pagel and Edmunds 1981). Furthermore, we also expect that because star formation is taking place at a low rate in these objects, the interstellar ultraviolet radiation field is lower than in normal spiral galaxies, thus preserving the carbon monoxide molecules.

III. ANALYSIS AND DISCUSSION

a) Preface

Our primary observational result is the data from a survey for $J = 1 \rightarrow 0$ CO emission from S0 and similar galaxies, a morphological type of galaxy that was, not long ago, thought to be devoid of star-forming gas. These observations complement the surveys for H I and dust emission cited in § I. Preliminary results of our program were presented by Thronson (1988), and some of the objects were discussed in the surveys of Kenney (1987), Kenney and Young (1988*a*), and Young *et al.* (1989). A decade ago, Johnson and Gottesman (1979) reported on an unsuccessful search for CO emission from this class of galaxies. More recently, Stark *et al.* (1986) included two members of this morphological type in their survey, and Verter (1983) detected the S0/a galaxy, NGC 7371. Just about the time that our paper is being published, Sage and Wrobel (1989) and Wiklind and Henkel (1989) will also present the results from their surveys of early-type disk galaxies.

b) The Ratio of Gas to Stellar Mass

Figure 3 shows the molecular gas mass versus the blue luminosity for the galaxies in our program, along with S0, S0/a, and Sa galaxies taken from the large survey of Young *et al.* (1989). The relation between the molecular or atomic mass and the visual luminosity (i.e., the stellar mass) has been investigated recently by Kenney (1987), Verter (1988), and Young *et al.* (1989). Although there is a wide variation in $M(H_2)/L_B$ for the galaxies shown in our figure, there appears to be a systematic change in the ratio over 3 orders of magnitude for which we have data (see Verter 1988 for a discussion of the uncertainties in a simple plot such as our Fig. 3). For the seven S0's from our survey, the least-squares best fit is $L_B \propto M(H_2)^{0.4}$. For comparison with other work in the literature, all S0, S0/a, and Sa galaxies in the figure were fitted by the line $L_B\ (L_\odot) = 5300\ M(H_2)^{0.62}$, with a correlation coefficient of 0.9, which is in rough agreement with our fit to the S0 galaxies alone, within the uncertainties. More usefully, our relation shows that the fractional molecular mass for our sample of early-type disk galaxies is given by $M(H_2)/L_B\ (M_\odot\ L_\odot^{-1}) \approx 10^{-6} L_B^{0.6}\ (L_\odot)$ over 3 orders of magnitude in the pair of quantities. In other words, if the CO line strength remains a consistent tracer of the molecular mass for all the early-type disk galaxies in our sample, H_2 appears to be relatively more abundant in the more luminous lenticulars and Sa's. Interestingly, the first large investigation into the variation of interstellar gas mass with galaxian luminosity seems to have been that of Roberts (1969), who found $M(\text{H I}) \propto L_{pg}^{0.69}$, very different from our result for the molecular mass.

Young *et al.* (1989) calculated a relationship for the molecular mass in a sample of primarily luminous late-type spirals that is very similar to the one that we derive (see also Stark *et al.* 1986 and Verter 1988). They suggested that the nonunity slope might be a consequence of greater visual extinction in galaxies with larger H_2 mass and central H_2 concentration. We consider this explanation to be unlikely, at least for the lenticular and S0/a galaxies, since these systems possess substantially less interstellar extinction on average than do spirals (e.g., Sandage and Tammann 1981). It therefore seems likely that more luminous systems simply contain a larger fractional molecular mass. We note, however, that the method of deriving $M(H_2)$ from L_{CO} ignores possible effects (metallicity, gas temperature, etc.) that may depend upon the luminosity of the galaxy and that may contribute to producing the relationship that we find.

As another explanation for the relation between $M(H_2)$ and L_B, we note that Young *et al.* (1989) found that more massive galaxies have higher central gas surface densities and, therefore, presumably a higher central volume density. Under these conditions, the nonunity slope in log L_B versus log $M(H_2)$ may be a consequence of a larger molecular gas fraction in galaxies with a higher average central gas density. Alternatively, more luminous galaxies of a given morphological type have been more efficient in using the available molecular gas for star formation on a large scale.

Faber and Gallagher (1976) used very general considerations to calculate that the annual mass return rate in sedate, non-

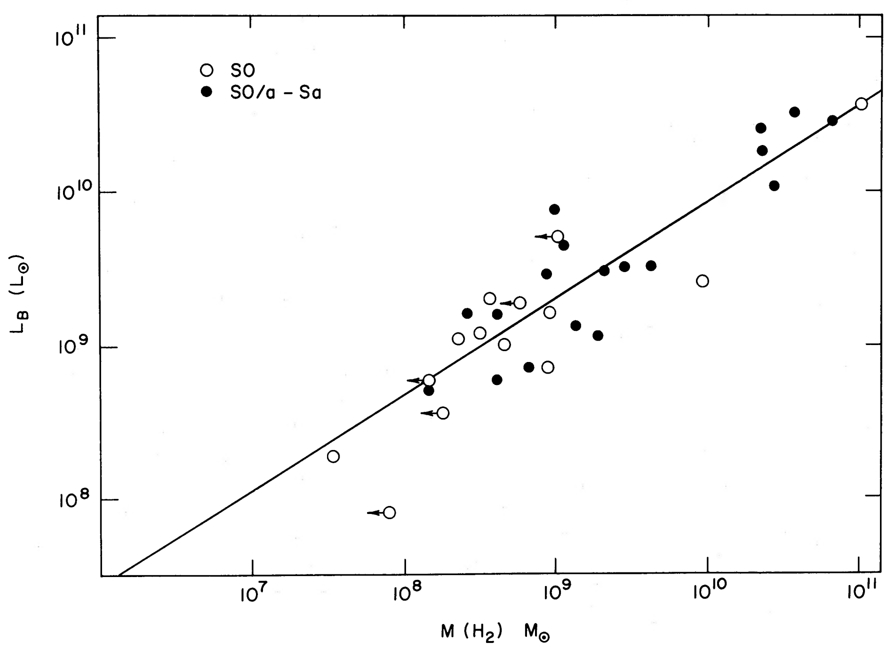

FIG. 3.—Derived molecular mass vs. blue luminosity (see our definition of L_B in § II*b*). The data for the two morphological types were taken both from our study and from that of Young *et al.* (1989). The line is $L_B\ (L_\odot) = 5300 M(H_2)^{0.62}$, the least-squares best fit for all the detected galaxies in the figure, and is discussed in § III*b*.

TABLE 3
DERIVED PARAMETERS

Object	Distance (Mpc)	L_{IR} ($L_\odot$)	L_B ($L_\odot$)	M_{H_2} ($M_\odot$)	M_d ($M_\odot$)	T_d (K)	$M_{H I}$ ($M_\odot$)
NGC 404......	4.6	0.14×10^9	0.19×10^9	0.34×10^8	0.46×10^5	33	2.5×10^8
NGC 693......	21	7.7×10^9	0.38×10^9	$\leq 1.7 \times 10^8$	13×10^5	37	9.8×10^8
NGC 1819.....	60	60×10^9	2.6×10^9	91×10^8	89×10^5	38	24×10^8
NGC 2273.....	26	11×10^9	3.0×10^9	9.0×10^8	23×10^5	36	14×10^8
NGC 2685.....	12	0.21×10^9	0.57×10^9	$\leq 1.4 \times 10^8$	2.7×10^5	27	11×10^8
NGC 3032.....	22	2.3×10^9	1.0×10^9	4.5×10^8	7.5×10^5	33	1.9×10^8
NGC 3226.....	18	6.3×10^9	0.85×10^9	$\leq 1.5 \times 10^8$	15×10^5	35	...
NGC 3413.....	8	0.16×10^9	0.08×10^9	$\leq 0.8 \times 10^8$	0.37×10^5	35	1.6×10^8
NGC 3593.....	8.3	3.3×10^9	0.7×10^9	6.6×10^8	6.5×10^5	36	1.3×10^8
NGC 3611.....	22	5.7×10^9	1.3×10^9	$\leq 13 \times 10^8$	8.3×10^5	38	10×10^8
NGC 4138.....	14	...	1.1×10^9	2.2×10^8	...	...	...
NGC 4383.....	20	7.6×10^9	0.6×10^9	4.0×10^8	7.8×10^5	41	25×10^8
NGC 4457.....	20	5.0×10^9	3.1×10^9	21×10^8	11×10^5	35	3.3×10^8
NGC 4459.....	20	2.0×10^9	2.0×10^9	$\leq 10 \times 10^8$	6.5×10^5	33	$\leq 0.09 \times 10^8$
NGC 4526.....	20	6.9×10^9	5.0×10^9	$\leq 10 \times 10^8$	28×10^5	32	$\leq 0.2 \times 10^8$
NGC 4710.....	20	6.7×10^9	1.6×10^9	8.8×10^8	22×10^5	33	0.28×10^8
NGC 4753.....	16	2.1×10^9	2.5×10^9	$\leq 2.9 \times 10^8$	11×10^5	31	...
NGC 5363.....	15	1.4×10^9	1.9×10^9	$\leq 5.4 \times 10^8$	8.4×10^5	30	1×10^8
NGC 5866.....	11	2.0×10^9	1.2×10^9	3.2×10^8	12×10^5	30	$\leq 2.5 \times 10^8$
NGC 7013.....	10	0.65×10^9	0.5×10^9	1.4×10^8:	4.6×10^5	29	4.5×10^8
NGC 7465.....	26	5.6×10^9	0.7×10^9	8.8×10^8	15×10^5	34	31×10^8:
NGC 7625.....	22	11×10^9	1.1×10^9	18×10^8	27×10^5	35	17×10^8

bursting galaxies is $\dot{M}_{rtn}$ ($M_\odot$ yr^{-1}) $\approx 10^{-10} L_B$ ($L_\odot$) within about a factor of 3. More detailed recent models generally support the relation found by Faber and Gallagher (Mathews 1989). Over a Hubble time of 15×10^9 yr, the mass lost by older stars should produce $M_{gas}/L_B \sim 1$–2 in solar units. Comparison with our results in Table 3 or in Figure 3 shows that this ratio is significantly in excess of the values for our survey galaxies, even when H I gas is included (Table 3 and next section; Wardle and Knapp 1986). We shall argue in §§ III*e* and III*f* that star formation is the most likely mechanism of depletion of the cool ISM in these galaxies. Furthermore, because of the relatively lower mass of the cool ISM in the low-luminosity lenticular galaxies, star formation may be taking place in an environment that is relatively more enriched in dust and heavy elements than is the case for luminous S0's and late-type spirals.

Many of the galaxies that show the highest ratio L_{CO}/L_B and, arguably, the largest relative molecular mass, are peculiar in some way, which makes interpretation of plots such as our Figure 3 uncertain. Of the S0 galaxies, NGC 1819 may be the most luminous member of a cluster, NGC 7465 appears to be one of a set of three neighboring galaxies, and Kenney (1987) argues that NGC 4710 may be a stripped spiral. In contrast, NGC 404, NGC 3032, and NGC 695 (Young *et al.* 1989) all have relative CO line strengths almost as large as the odd galaxies, but they are themselves apparently normal. In addition, it is difficult to estimate the effects of upper limits in the preceding analysis. Five early-type galaxies with upper limits are included in our plot. Two have ratios $L_B/M(H_2)$ that fall below our best-fit line, while three fall above it. We conclude that inclusion of these five objects would have little effect on our discussion. In contrast, a much more serious effect is a consequence of our selection of H I– or *IRAS*–detected galaxies for inclusion in our survey. It is reasonable to expect that galaxies that possess a detectable atomic or cool dust component in their ISM will also be more likely to contain molecular mass. It is not at all clear that this effect produces the relationship shown in our Figure 3, since the relation covers a very wide range in visual luminosity, and nearly the same slope in the relation between L_B and $M(H_2)$ has been reported for both early- and late-type disk galaxies. However, as important as it is to understand the dependence of the mass of the ISM on the size and morphology of galaxies, a complete study must await a CO survey that is less susceptible to systematic errors than ours.

c) The Ratio of Molecular to Atomic Gas Mass

Although a widely accepted, generally applicable theory of the relationship between H_2 and H I gas has yet to be produced, it is commonly believed that this pair of components of the ISM are closely related. It is sometimes suggested, for example, that the atomic gas is the reservoir for molecular cloud creation, although the observational and theoretical support for this idea is limited (e.g., Kenney 1987; Kenney and Young 1988*b*). Most work on the evolution of the cool ISM has concentrated on spiral galaxies, and it is usually suggested that their structure plays a major role in creating and maintaining the balance between molecular and atomic gas; this has been discussed in the context of CO observations by Stark, Elmegreen, and Chance (1987) and Verter (1988).

To date, the most comprehensive compilation of atomic and molecular masses for luminous ($L_B \geq 10^8$ $L_\odot$) disk galaxies is that of Young *et al.* (1989). Using 42 Sbc and later galaxies in a variety of environments with derived total H I and H_2 masses from their survey, we find a least-squares best fit to the relation between thse two components of $M(H_2) \propto M(\text{H I})^{0.94}$. In other words, over about 3 orders of magnitude in these quantities, the average value for $M(H_2)/M(\text{H I})$ changes very little, if at all, in nearly normal late-type spirals. Stark *et al.* (1986) found similar results for a handful of galaxies well away from the center of the Virgo Cluster, while Verter (1988) undertook a more detailed study of a smaller number of galaxies and produced a similar relation. For low-luminosity spirals Kenney and Young (1988*b*) found a much lower average value for $L_{CO}/M(\text{H I})$ and argued that this is a consequence of a lower

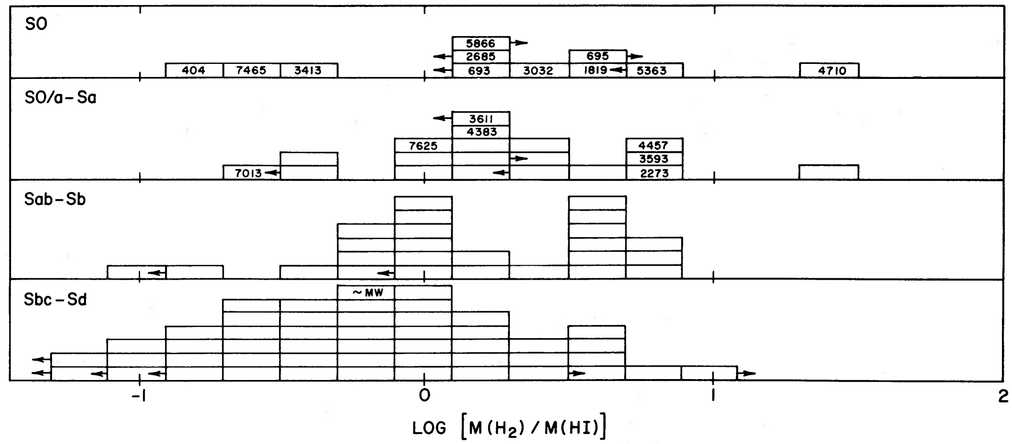

FIG. 4.—Ratio of molecular to atomic gas mass derived for the early-type disk galaxies in this study and the spirals studied by Young *et al.* (1989). Limits are 2 σ and are shown by arrows. The estimated value for the Milky Way is also shown.

H_2/H I mass ratio, although perhaps a decrease in $L_{CO}/M(H_2)$ is important for these objects (see also Maloney 1987; Maloney and Black 1988).

Figure 4 shows a histogram of calculated values for the cool gas mass ratio for the early-type disk galaxies in our survey and includes results from the Young *et al.* (1989) survey. The dominant feature of Figure 4 is a large range in the ratio for all morphological types. We also find evidence for a higher ratio of $M(H_2)/M$(H I) in S0, S0/a, and Sa galaxies than in late-type spirals, which appears to contradict the results in Verter (1988). Our results are also in conflict with the conclusions of Pompea and Rieke (1989), who argued that Sa galaxies have suppressed large-scale formation of H_2 relative to H I. However, the small number of objects in the various studies and the uncertainties in the conversion of CO line strength to H_2 mass make this conclusion tentative. Also, the fact that our sample consists primarily of infrared-selected objects may be related to the likelihood of detecting molecular mass. Finally, the two S0's with the highest ratios of molecular to atomic mass are in the Virgo Cluster and may have been stripped of their atomic gas (Kenney and Young 1989). Another conclusion that we might draw from our data is that the relative global abundance of the two dominant components of the cool phase of the ISM is not a strong function purely of morphological type. Apparently, early-type disk galaxies without spiral structure and possessing a low-mass cool ISM can have a relatively large ratio $M(H_2)/M$(H I).

d) Dust in Early-Type Disk Galaxies

With the availability of data from *IRAS*, a large number of elliptical and lenticular galaxies have been found to contain warm interstellar dust (e.g., Jura 1986; Jura *et al.* 1987; Thronson and Bally 1987*a*; Dressel 1988; Wrobel and Heeschen 1988; Bally and Thronson 1989; Knapp *et al.* 1989; Walsh and Knapp 1989). These observations have contributed to a growing realization that many early-type galaxies are not as exhausted of dust and cool gas as had been widely believed, and perhaps star formation is active within at least some of them.

Flux densities at 60 and 100 μm from "line-add" analysis of *IRAS* data are presented in Table 1. (For a discussion of our use of the "line-add" programs see Thronson, Bally, and Hacking 1989 or Bally and Thronson 1989.) Table 3 includes the far-infrared luminosity of the galaxies in the band 40–125 μm, derived via

$$L_{IR}(L_\odot) = 5.6 \times 10^5 D^2(\mathrm{Mpc})[2.58F_{60}(\mathrm{Jy}) + F_{100}(\mathrm{Jy})] , \quad (5)$$

as suggested by Lonsdale *et al.* (1985). There are a number of uncertainties in this calculation, which include (1) calibration uncertainties, estimated to be about $\pm 10\%$; (2) uncertainties in the particular choice of method of adding *IRAS* satellite scans, estimated to be about $\pm 20\%$ (e.g., Thronson, Bally, and Hacking 1989); and (3) the uncertainty inherent in adopting a color correction to the *IRAS* flux densities that can only be an approximation to the true spectral energy distribution. Also included in Table 3 is an estimate of the average temperature of the dust that dominates the emission at wavelengths between 60 and 100 μm. It was derived by assuming that the spectrum of the source followed $F_\nu \propto \nu B_\nu(T_d)$. As discussed by Thronson and Bally (1987*a*) and Thronson, Bally, and Hacking (1989), the far-infrared spectra of S0's are similar to those found for more dust-rich spirals, indicating that the dominant source of the dust emission in the lenticulars may also be dust mixed with molecular material and with the diffuse interstellar medium. However, these authors argued that because star formation is relatively less active in lenticulars than in spirals, it is likely that the contribution to the total far-infared emission from regions of stellar creation is likely to be much less than in the case for late-type spirals or irregulars. In addition, since the mass of the cool ISM in most lenticulars is low, several alternative sources of infrared emission may be important in these galaxies: circumstellar dust emission from evolved stars and emission from active nuclei.

Little significance should be attached to the particular temperatures derived for any of these galaxies or, especially, to the narrow range over which they fall: 60 and 100 μm observations are sensitive only to a small range of dust temperatures and, presumably, physical conditions. As argued by Thronson and Bally (1987*a*), it is likely that these dust temperatures are not, strictly speaking, measures of an actual temperature, but rather are measures of the relative abundance of major components of the ISM. Early-type galaxies can be luminous at shorter wavelengths, indicating hot dust (Jura *et al.* 1987; Thronson and Bally 1987*a*; Walsh and Knapp 1989; Thronson, Bally, and Hacking 1989), and at submillimeter wavelengths (Hunter *et al.* 1989), indicating abundant cool material.

Table 3 also lists the mass of dust in emission at about 100 μm, derived using

$$M_d(M_\odot) = 5D^2(\text{Mpc})F_{100}(\text{Jy})[\exp(144/T_d) - 1], \quad (6)$$

adapted from Thronson and Telesco (1986). This equation is insignificantly different from that adopted by Young *et al.* (1989) for their large study of predominantly spiral galaxies.

Using the data in Table 3, we estimate an average value for the gas-to-dust mass ratio, M_{gas}/M_d, where the gas mass is the sum of the atomic and molecular components. We assume that some dust is mixed with the hot X-ray–emitting gas (§ III*f*), but for now we shall assume that this component is substantially less massive than the cool components of the ISM. For the nine S0's for which we have sufficient data, we calculate an average value for M_{gas}/M_d to be 1600, with a standard deviation of about a factor of 2.5. The S0/a and Sa galaxies in our sample have a ratio nearly identical to that of the S0's. These values are very different from the canonical value of around 100 derived primarily from visual work and theoretical understanding of the heavy-element abundance in the ISM. The usual explanation for this difference is that the dust in emission at 100 μm represents only a small fraction of the total dust mass. Moreover, there are probably systematic uncertainties in the formula used to calculate M_d.

A small number of galaxies in our survey have only upper limits to either the atomic and/or the molecular gas mass. For these objects, the limit to the gas-to-dust mass ratio averages about 800. Inclusion of these objects would slightly lower our estimate of the average ratio for the objects in our sample.

Note that the ratio we derive here is 3 times higher than that derived by Young *et al.* (1989) for the ratio $M(H_2)/M_d$ in their survey of infrared-bright spirals. If the dust is mixed uniformly with the atomic and molecular gas (e.g., Stark *et al.* 1986; Knapp, Helou, and Stark 1987; Boulanger and Perault 1988), and the H I and H_2 masses are comparable (previous section), then the value of M_{gas}/M_d that Young *et al.* would have derived would be similar to that which we find for the lenticulars and Sa galaxies. However, Young *et al.* concluded that the far-infrared emission (and presumably the dust from which it arises) was more closely associated with the molecular than with the atomic gas in their sample of spirals. In contrast, Boulanger and Perault found that for the solar neighborhood of the Milky Way, the 100 μm emission is closely associated with the H I gas. Selection effects in the survey by Young *et al.* favor galaxies with strong far-infrared emission and, perhaps, a relatively greater dust mass than is the case with our survey or with a typical location in the disk of the Milky Way. We also repeat that a significant fraction of the dust emission from some early-type galaxies can arise in material (e.g., active nuclei, circumstellar material) not associated with the general ISM (Bally and Thronson 1989; Thronson, Bally, and Hacking 1989). Nevertheless, given the scatter in the values derived for individual galaxies, we conclude that our gas-to-dust mass ratio for the cool ISM in early-type disk galaxies is within a factor of 2 or 3 of that found for late-type disk galaxies.

A nearly normal gas-to-dust ratio argues against a source for the cool ISM that is external to the galaxy. Intergalactic gas clouds and low-mass dwarf galaxies have been suggested to be the source of a cool ISM for lenticulars (e.g., Wardle and Knapp 1986). These are presumably heavy-element–poor and should show little CO or thermal dust emission. Once again, the most straightforward description of the cool ISM in lenticulars in our survey is remnant material from the formation of the system, enriched by mass loss by evolved stars and depleted by star formation.

e) Star Formation: Its Rate and Efficiency in Lenticular Galaxies

A major goal of this program was to estimate the mass of star-forming molecular material within S0 galaxies and to obtain an estimate of the efficiency of star formation for comparison with disk galaxies with spiral structure. We have successfully completed the former task, but estimating the numbers of newly formed stars for comparison with the mass of gas from which they were born is difficult with the data available to us.

Three techniques are commonly employed to estimate star formation rates (e.g., Kennicutt 1986): (1) stellar population synthesis schemes, usually attempting to fit blue or ultraviolet spectra with a young-star component (e.g., Gunn, Stryker, and Tinsley 1981; Véron and Véron-Cetty 1985; O'Connell 1986*b*; Burstein, Krumm, and Salpeter 1987; Gregg 1989); (2) direct observation of nonnuclear visual-line emission from material surrounding hot, newly formed stars (e.g., Kennicutt 1983; Balkowski, Alloin, and Le Denmat 1986; Phillips *et al.* 1986; Pogge and Eskridge 1987; Hunter *et al.* 1989; Kim 1989); and (3) analysis of the far-infrared emission purported to be from dust heated by young stars (e.g., Jura 1986; Persson and Helou 1987; Thronson and Bally 1987*a*; Thronson, Bally, and Hacking 1989; Pompea and Rieke 1989). Each technique has advantages, and all have been attempted with S0's. For the techniques, the primary disadvantage may be summarized as "uniqueness": other activity—nuclear emission, photospheric emission from horizontal branch stars, infrared flux from inert "cirrus"—can closely mimic the appearance of moderately active star formation. However, most authors have concluded that, for at least some lenticulars, star formation is taking place at present.

Because of the contamination of the far-infrared emission from star-forming material in lenticulars by the emission from dust associated with H I gas, active nuclei, or circumstellar emission (previous section), use of the total infrared luminosity to estimate a star formation rate (SFR) or star formation efficiency (SFE) may not be justified in general. Considering other techniques, to our knowledge only four galaxies in our survey have also had total nonnuclear Hα line luminosities determined: NGC 4138 and NGC 7013 (both by Pogge and Eskridge 1987), NGC 3032 (Gallagher, Hunter, and Tutukov 1984), and NGC 3593 (Hunter *et al.* 1989). Observed and derived values for these four systems are presented in Table 4. Because of the low interstellar absorption expected for the galaxies in our program, we assume that the observed Hα line flux is unaffected by absorption within the program galaxy. However, it is possible that extinction is significant from dust that is local to the ionized gas and associated young stars.

Determination of star formation rates using visual line flux has been discussed by a number of authors (e.g., Kennicutt 1983; Kennicutt and Kent 1983; Gallagher, Hunter, and Tutukov 1984). Assuming a Salpeter initial mass function (IMF) from 0.1 to 100 $M_\odot$, the total stellar mass formation rate is $\dot{M}_{H\alpha}$ ($M_\odot$ yr^{-1}) = $3.9 \times 10^{-8} L_{H\alpha}$ ($L_\odot$). This relation is within about 10% of that derived by Kennicutt (1983) for an IMF found by fitting the visual colors of spiral galaxies. Only the small number of very luminous stars contribute to exciting the interstellar gas, but our equation is an estimate of the

TABLE 4

STAR FORMATION RATES, EFFICIENCIES, AND LIFETIMES

Object (1)	$L_{H\alpha}$ $(L_\odot)$ (2)	$\dot{M}_{H\alpha}$ $(M_\odot\ yr^{-1})$ (3)	$M_{*,H\alpha}$ $(M_\odot)$ (4)	ϵ (%) (5)	τ_R (yr) (6)	References (7)
NGC 3032.....	12×10^6	0.45	9.5×10^5	0.2	1.4×10^9	1
NGC 3593.....	19×10^6	0.75	15×10^5	0.2	1.1×10^9	2
NGC 4138.....	2.5×10^6:	0.09:	2×10^5:	0.09:	$\geq 2.5 \times 10^9$	3
NGC 7013.....	4.1×10^6	0.15	3×10^5	0.2:	4×10^9	3

Col. (3).—Star formation rate assumes Salpeter IMF from 0.1 to 100 $M_\odot$: $\dot{M}_{H\alpha}$ ($M_\odot$ yr^{-1}) = 3.9×10^{-8} $L_{H\alpha}$ ($L_\odot$) (Kennicutt 1983; Gallagher, Hunter, and Tutukov 1984; Thronson and Telesco 1986).

Col. (4).—Mass of young stars assumes Salpeter IMF from 0.1 to 100 $M_\odot$: $M_{*,H\alpha}$ $(M_\odot) = 0.078 L_{H\alpha}$ $(L_\odot)$.

Col. (5).—Efficiency of star formation derived from the mass of young stars and the molecular mass from Table 3, $\epsilon = M_{*,H\alpha}/M(H_2)$.

Col. (6).—τ_R is the "Roberts time," the *e*-folding time for depletion of the cool ISM, and is calculated via $\tau_R = [M(H_2) + M(H\ I)]/\dot{M}_*$.

NOTE.—Distances adopted from Table 3.

REFERENCES FOR THE Hα FLUXES.—(1) Gallagher, Hunter, and Tutukov 1984; (2) Hunter *et al.* 1989; (3) Pogge and Eskridge 1987.

stellar mass formation rate for all stars. The Hα luminosities from the literature are included in our table, along with the derived star formation rates, which are seen to range over almost an order of magnitude. For the same IMF, the mass of young stars may be estimated as M_* $(M_\odot) = 0.078 L_{H\alpha}$ $(L_\odot)$, allowing an efficiency of stellar creation to be estimated, $\epsilon = M_*/M(H_2) = 0.078 L_{H\alpha}/M(H_2)$ in solar units, which is included in our table.

For comparison, if we assume that the far-infrared luminosity arises only from young stars, we may derive a SFR via $\dot{M}_{IR}$ ($M_\odot$ yr^{-1}) = $6.5 \times 10^{-10} L_{IR}$ $(L_\odot)$, again assuming a Salpeter function from 0.1 to 100 $M_\odot$ (Thronson and Telesco 1986; see the detailed discussions in Persson and Helou 1987 and Leisawitz and Hauser 1989 on the uncertainties of using the far-infrared emission as a measure of the star formation rate.) As luck would have it, NGC 4138 was not included in the sky coverage of *IRAS*, but the far-infrared luminosities of NGC 3032, NGC 3593, and NGC 7013 all indicate SFRs roughly a factor of 3 above that derived from the Hα emission, were all the infrared flux to arise from young stars. This is not likely to be the sole source of infrared emission for any of the objects in our survey, so a stellar mass-creation rate derived from far-infrared observations is an upper limit to the true SFR. At the same time, a SFR derived from the Hα emission might be low as a consequence of dust obscuration, either within the Milky Way or within the observed galaxy. Considering these uncertainties, an agreement between the SFR derived from the infrared observations and the emission-line data to within a factor of 3 is surprisingly good. However, we consider the visual-line flux to be more accurate, and star formation rates derived from far-infrared observations are upper limits for these galaxies.

Using the visual-line luminosities, our Table 4 shows that the efficiencies of star formation, ϵ, are similar for all four galaxies. With the exception of the uncertain value for NGC 4138, the efficiencies as we have here defined them are all 0.2%. Because of the serious systematic uncertainties in any derivation of the efficiency, it is probably most useful to use ϵ in a relative way, comparing with values derived in the same way for other galaxies. Using the Hα observations of primarily late-type spirals in Kennicutt and Kent (1983) and the molecular masses in Young *et al.* (1989), we derive an average value for $L_{H\alpha+N\ II}/M(H_2)$ of $1.3 \times 10^{-2} L_\odot/M(H_2)$, with a standard deviation of about a factor of 3. This average translates into an efficiency of about 0.1% using our formulation. We consider this to be in good agreement with that derived for our small sample of early-type galaxies (Table 4), given the large variation in values among objects. The agreement would probably be improved with a correction to the data from Kennicutt and Kent for the visual extinction within their observed spiral galaxies, a problem which is likely to be less serious for the gas- and dust-poor lenticulars.

Based on the available data, there seems to be little evidence at present for significant differences between star formation per unit molecular mass (the efficiency) in gas-poor (S0) and in gas-rich (late-type spiral) galaxies. Based on our limited sample, the global SFR appears to depend linearly on the total H_2 mass. The most straightforward consequence of this is that the rate of star formation then varies linearly with surface density as suggested for spirals by Young and Scoville (1982) and Tacconi and Young (1987), SFR $\propto \sigma$. This contrast with a more commonly adopted "Schmidt law" for the large-scale rate of star formation, SFR $\propto \sigma^n$, with $n \approx 2$.

We estimate the time remaining before the ISM has been significantly depleted by star formation in these objects, sometimes called the "Roberts time," τ_R. If we assume that the cool ISM is depleted as a function of time following $M_{gas}(t) \propto \exp(-t/\tau_R)$, and if the star formation rate is equal to the ISM depletion rate, as seems a good approximation, then $M_{gas}/\dot{M} = \tau_R$. Using Tables 3 and 4, we find $\tau_R = (1–4) \times 10^9$ yr, substantially shorter than a Hubble time. This range of time is about equal to that derived for many spirals and irregulars (Larson, Tinsley, and Caldwell 1980; Kennicutt 1983, Thronson and Telesco 1986.; Thronson and Bally 1989). Again using the H_2 and H I data in Young *et al.* (1989) and the Hα fluxes in Kennicutt and Kent, we derive an average value for $\tau_R = M_{gas}/\dot{M}$ of 4×10^9 yr for late-type spirals, insignificantly different from our result for the S0's. This close agreement for time scales is primarily another way of stating that the efficiency of star formation is roughly the same in all galaxies considered. That is, rearranging the formulations from above, $\epsilon = 0.078 L_{H\alpha}/M(H_2) = 2.0 \times 10^6 \dot{M}/M(H_2) = 2.0 \times 10^6/\tau_R$. Thus, for τ_R roughly a few billion years for a wide range of galaxies, $\epsilon \sim 0.1\%$, as we just derived.

f) *X-Ray Emission from Lenticulars: Refueling the ISM?*

A major revelation about the ISM within early-type galaxies was the detection of strong X-radiation from a large number of normal systems, including S0's (e.g., Nulsen, Stewart, and Fabian 1984; Forman, Jones, and Tucker 1985; Fabbiano 1986; Canizares, Fabbiano, and Trinchieri 1987; Fabbiano, Gioia, and Trinchieri 1988). We adopt one interpretation of these observations in which high-temperature gas lost by evolved stars is trapped in the gravitational potential well of early-type galaxies and is the source of the X-ray emission. This conclusion has been supported in part by the reasonable agreement between the rate at which the hot gas is cooling and the rate at which it is calculated to be replenished (e.g., Forman, Jones, and Tucker 1985). However, for many galaxies it is very possible that strong X-ray emission can come from discrete stellar sources, rather than from widely distributed hot gas. It has often been suggested that, if the source is hot gas, over a Hubble time sufficient mass might be lost by evolved stars to replenish a depleted ISM. Indeed, Faber and Gallagher (1976) estimated a mass return rate of $\dot{M}$ ($M_\odot$ yr^{-1}) $\approx 10^{-10}$ L_B ($L_\odot$) with about a factor of 3 uncertainty for stars in galaxies, which, if the material can be preserved, will result in $M_{\rm gas}/L_B \sim 1$–2 $M_\odot$ $L_\odot^{-1}$ over the time since the galaxy was born (see also Mathews 1989). This amount of gas is comparable to that found for gas-rich, late-type spirals and merely emphasizes the well-known importance of mass return to the evolution and current state of the ISM in galaxies such as the Milky Way. Because this ratio significantly exceeds that which we derive for the early-type disk galaxies, we suggested in the previous section that star formation at a rate of only ~ 0.1 $M_\odot$ yr^{-1} can be an effective sink for the gas in lenticulars and, perhaps, ellipticals as well. We shall assume that all of the X-ray emission from the galaxies in our sample arises from a hot interstellar component rather than from discrete sources.

X-ray observations are available for five of the galaxies included in our program, the first early-type galaxies for which all major components of the ISM—dust and hot and cold gas—have been observed. These objects are listed in Table 5 and include two normal S0 galaxies (NGC 4459 and NGC 5866), a normal probable S0/a (NGC 3593), the Spindle (NGC 2685), and the peculiar early-type galaxy NGC 4753. Despite the variety in this small sample, our general conclusions concerning their X-ray emission and ISM refueling via evolved stars are the same for all of them.

In the table we list the X-ray (0.5–4.5 keV) luminosity of each object and estimate the mass of hot gas associated with that emission if the source of the X-ray emission is hot gas rather than stellar sources. Accurately deriving $M_{\rm hot}$ requires more information than we have for the objects in our sample. In particular, it requires knowledge of the spatial distribution of X-ray emission. Without this, we have instead used the detailed observations in Forman, Jones, and Tucker (1985) to find an average relation between X-ray luminosity and $M_{\rm hot}$ for a variety of S0 and elliptical galaxies. In essence, we have assumed that the distribution of hot gas in our sample of galaxies is the same, on average, as that in early-type galaxies for which the distribution has been determined. From the Forman, Jones, and Tucker sample, we find $M_{\rm hot}$ ($M_\odot$) $\leq 3.2 \times 10^2 L_X$ ($L_\odot$), with a variation of plus or minus a factor of 2. The limit is a consequence of the possibility that discrete stellar sources contribute to the X-ray emission.

The cooling rate of the hot gas was estimated from the formulation in Nulsen, Stewart, and Fabian (1984), $\dot{M}_{\rm cooling}$ ($M_\odot$ yr^{-1}) $\leq 2\mu m_{\rm H} L_X/3kT \approx 6.2 \times 10^{-8} L_X$ ($L_\odot$) for a gas temperature of 10^7 K. Again, the limit obtains in the event that discrete sources contribute to the observed X-ray flux. Our table also includes the estimated mass return rate from evolved stars, $\dot{M}_{\rm rtn}$, from the Faber and Gallagher (1976) formulation and the SRF as estimated from the far-infrared observations, $\dot{M}_{\rm SF,\,IR}$ (Thronson and Telesco 1986). As discussed in the previous section, this SFR may overestimate the true stellar creation rate because of the heating of the cool ISM by sources other than luminous young stars. However, with the exception of NGC 3593, no alternative estimates of the SFR in the galaxies for which we have X-ray data are known to us.

Comparison of Table 5 with Table 3 shows that the hot gas makes up a substantial fraction of the ISM in all five galaxies, although the relative abundance of the components of the ISM varies significantly. Furthermore, in four galaxies, the total (hot and cool) interstellar gas mass is within a factor of only about 2 of that expected to accumulate over a Hubble time (i.e., $M_{\rm gas}/L_B \approx 1$–2 in solar units), using the estimated stellar mass return rate (col. [5] in Table 5). The exception, NGC 4753, has

TABLE 5

X-RAY GALAXIES

Object (1)	L_X ($L_\odot$) (2)	$M_{\rm hot}$ ($M_\odot$) (3)	$\dot{M}_{\rm cooling}$ ($M_\odot$ yr^{-1}) (4)	$\dot{M}_{\rm rtn}$ ($M_\odot$ yr^{-1}) (5)	$\dot{M}_{\rm SF,\,IR}$ ($M_\odot$ yr^{-1}) (6)
NGC 2685.....	4.8×10^5	$\leq 1.6 \times 10^8$	≤ 0.03	0.06	≤ 0.14
NGC 3593.....	5.9×10^5	$\leq 1.9 \times 10^8$	≤ 0.04	0.07	≤ 2.1
NGC 4459.....	20×10^5	$\leq 6.4 \times 10^8$	≤ 0.12	0.2	≤ 1.3
NGC 4753.....	12×10^5	$\leq 3.9 \times 10^8$	≤ 0.08	0.5	≤ 1.4
NGC 5866.....	7.2×10^5	$\leq 2.3 \times 10^8$	≤ 0.05	0.12	≤ 1.3

Col. (3).—$M_{\rm hot}(M_\odot) \leq 3.2 \times 10^2 L_X (L_\odot)$; see § III*f*.

Col. (4).—$\dot{M}_{\rm cooling}(M_\odot$ yr$^{-1}) \leq 2\mu m_{\rm H} L_X/3kT \approx 6.2 \times 10^{-8} L_X$ ($L_\odot$); Nulsen, Stewart, and Fabian 1984).

Col. (5).—$\dot{M}_{\rm rtn}(M_\odot$ yr$^{-1}) = 10^{-10} L_B (L_\odot)$; Faber and Gallagher 1976.

Col. (6).—$\dot{M}_{\rm SF,\,IR}(M_\odot$ yr$^{-1}) \leq 6.5 \times 10^{-10} L_{\rm IR} (L_\odot)$; Thronson and Telesco 1986.

NOTE.—See discussion in § III*f*. Upper limits for $M_{\rm hot}$ and $\dot{M}_{\rm cooling}$ are due to the possibility of the X-radiation is supplied by stellar sources. The upper limit to $\dot{M}_{\rm SF,\,IR}$ is a consequence of sources of far-infrared emission other than star formation. References for X-ray data: for NGC 2685, NGC 4459, NGC 4753, NGC 5866, Canizares, Fabbiano, and Trinchieri 1987; for NGC 3593, NGC 4753, Fabbiano, Gioia, and Trinchieri 1988.

no H I mass determined for it, to our knowledge. Also, the cooling rate of the hot gas (col. [4]) is within a factor of 2 of the mass return rate (col. [5]) in four of the galaxies. This agreement is well within the uncertainties expected for the calculations and supports earlier conclusions that highly evolved stars are the ultimate source for the hot interstellar gas in our sample of galaxies.

It is tempting to conclude further that the mass returned by these stars also is the primary fuel for stellar creation, particularly since we are limited by no direct measure of the star formation rates in these objects. However, our upper limits to the SFR from the far-infrared data (col. [6]) are very substantially larger than either the rate of cooling or the rate of mass return in most of the cases in Table 5. The exception, again, may be the peculiar galaxy NGC 4753. For one galaxy, NGC 3593, with an SFR estimated from the more reliable Hα data (Table 4), the SFR exceeds the mass return rate by a large factor. Based on available information, we conclude that the ISM is being consumed in this small sample of galaxies at a rate substantially in excess of that at which it is being replenished by mass loss.

We have contended, however, that we believe that our sample of S0 and S0/a galaxies may not be fully representative of these morphological types. In particular, the selection criteria in our observing list were probably weighted toward galaxies with at least a moderately massive ISM and/or active, if low-level, star formation. Given that there is likely to be a broad continuum of properties for early-type disk galaxies, there are almost certainly a large number of lenticular galaxies within which star formation is balanced by mass return, $\dot{M}_{\rm SF} \approx \dot{M}_{\rm rtn}$. Bearing in mind our repeated warnings that the infrared luminosity is by no means an unambiguous measure of the star formation rate, and stellar sources can contribute significantly to the X-ray emission, *candidate* early-type galaxies in which the current star formation rate may be roughly balanced by mass return can be identified by equation $\dot{M}_{\rm cooling}$, $\dot{M}_{\rm rtn}$, and $\dot{M}_{\rm SF,\,IR}$, which gives the simple relations (see the notes to Table 5)

$$L_{\rm IR}/L_X \sim 95 \;, \quad L_{\rm IR}/L_B \sim 0.15 \;. \qquad (7)$$

The first equation indicates that the X-ray cooling rate is balanced by the star formation rate, while the second obtains under the condition that the mass return rate is equal to the cooling rate. All of the objects in Table 5 have ratios that exceed these values by a significant factor, which is equivalent to finding that the value in column (6), $\dot{M}_{\rm SF,\,IR}$, exceeds those in column (4), $\dot{M}_{\rm rtn}$, and column (5), $\dot{M}_{\rm cooling}$, by a large factor. In addition, most, but not all, of the objects in our CO survey have infrared-to-blue ratios significantly in excess of 0.15. Most of the early-type disk galaxies in our sample have an ISM that, presumably, either is largely a remnant from the creation of the galaxy or else was acquired externally.

Knapp *et al.* (1989), Walsh and Knapp (1989), and Bally and Thronson (1989) compiled $L_{\rm IR}/L_B$ for large numbers of lenticular galaxies. Both samples had a large fraction of the objects with ratios in excess of our criterion in equation (6), indicating a star formation rate that plausibly is in excess of the mass return rate. At the same time, however, both studies found another significant fraction with the ratio close to or slightly less than our criterion. However, both the Walsh and Knapp sample and the Bally and Thronson sample had a few or no objects with $L_{\rm IR}/L_B$ significantly less than our value in equation (6). Mass return from highly evolved stars sets a minimum value for the infrared-to-blue flux ratio, and it is likely that the sensitivity of the infrared survey to date has been insufficient to study the population of visually luminous lenticulars harboring star formation fueled by gas supplied predominantly by mass lost by evolved stars.

IV. SUMMARY

We have presented and discussed the results of a millimeter-wave CO survey of S0 and S0/a galaxies. The success of our survey demonstrates that molecular gas exists within some members of a class of galaxies that was once thought to be devoid of interstellar media and star formation. We conclude the following from our study:

1. *Molecular gas is abundant within some early-type disk galaxies.*—Typical ratios of molecular gas to stellar mass in our sample are around an order of magnitude less than those found in late-type spirals of about the same visual luminosity. although a small number of lenticular galaxies have fractional gas masses that approach those found for Sb and Sc galaxies. Early type galaxies with the largest ratio $L_{\rm CO}/L_B$ tend to be peculiar in some way.

2. *The range in the ratio of molecular gas to atomic gas mass is similar to those in other disk galaxies.*—We found $M({\rm H_2})/M({\rm H\,I})$ to have an average value of about unity for the objects in our sample, but the derived ratio varies by about an order of magnitude on either side of this mean, about the same range as found for spiral galaxies. We conclude that the morphology of a galaxy may be only one effect on the global mass ratio of H_2 to H I.

3. *In the S0 and S0/a galaxies that we studied, estimated rates of star formation are substantially smaller than, but efficiencies of star formation are roughly the same as, those in Sb or Sc galaxies.*—In the case of the rate of star formation, this difference is due largely to the smaller amount of fuel (H_2 gas) that is available. We find no strong effect of galaxy morphology on the global efficiency of star formation for the small sample of galaxies for which we have data. For a large number of galaxies with a wide range of morphologies, the *e*-folding time for depletion of the interstellar gas is a few billion years, which we interpret as a consequence of the similar efficiency of star formation for a wide range of galaxian environments.

4. *Although the rate of cooling of the hot, X-ray emitting gas may be close to the estimated stellar mass return rate in our sample, the star formation rate probably exceeds both by a significant factor.*—Over a Hubble time, the total mass returned to the ISM is likely to be in excess of the amount that we estimate is currently present. However, since the star formation rate is much higher than the mass return rate in objects for which we are able to estimate both rates, lenticular galaxies in our sample can be kept gas-poor.

We appreciate the fine support of the staff of the Five College Radio Astronomy Observatory, the National Radio Astronomy Observatory, and the Infrared Processing and Analysis Center. We have benefited from useful conversations with John Bally, Steve Pompea, Jacqueline van Gorkom, and Fran Verter. Millimeter-wave astronomy at Five Colleges is supported by the National Science Foundation H.A.T. and M.A.G. were supported by NASA Grant NAG 2-134.

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