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THE COOL ISM IN ELLIPTICAL GALAXIES. I. A SURVEY OF MOLECULAR GAS

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ABSTRACT

We present preliminary results from a survey of CO emission from members of a volume-limited sample of noncluster elliptical galaxies. Our intent is to compare the gas properties of these ellipticals to a sample of lenticulars selected using similar criteria. The data, although still sparse, suggest that the cool gas in ellipticals shows the same puzzling upper mass cutoff found in the lenticular galaxies. We find, however, significantly lower detection rates and possibly much lower H_2/H I mass ratios in the ellipticals. The detection rate is higher among the lower mass galaxies, as has been found previously. This seems puzzling given that the deeper potential wells of the larger galaxies ought to make gas retention easier, but perhaps that effect is overwhelmed by feedback from the central supermassive black hole. As we have observed ~40% of our full sample, the conclusions are necessarily tentative at this time.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: ISM

1. INTRODUCTION

There is as yet no clear, coherent, and complete explanation for the origins of elliptical galaxies and their gas contents. Since the early numerical simulations of Toomre & Toomre (1972) it has been evident that mergers between spirals can produce objects whose structure resembles that of an elliptical galaxy (e.g., Barnes & Hernquist 1992; Naab & Burkert 2003). One current view is that bright ellipticals come from early, major mergers between disks (e.g. Naab et al. 1999; Naab & Burkert 2003). Minor mergers, those involving mass ratios of roughly 3:1 and larger, probably formed the fainter galaxies, those with disk components and large rotational speeds. In all cases some dissipation appears to be needed (e.g., Barnes & Hernquist 1996; Shioya & Bekki 1998; Cretton et al. 2001; Robertson et al. 2006; Naab et al. 2006a), especially for making fainter galaxies, but how much is not clear. To further complicate the situation, it is becoming clear that mergers between gas-poor objects have contributed importantly to the growth of many luminous ellipticals (van Dokkum 2005; Naab et al. 2006b; Bell et al. 2006; Boylan-Kolchin et al. 2006), the so-called dry or red merger hypothesis. On the other hand, the classical monolithic formation idea has refused to die; a modified version suggested by Kormendy (1989) and Kobayashi (2004) is still attractive for explaining radial gradients in absorption line strengths (Ogando et al. 2005).

There is not yet even clear agreement on the observed properties of ellipticals, especially the properties of their interstellar media. For example, Lees et al. (1991) and Knapp & Rupen (1996) found molecular gas in about half of the *IRAS*-selected galaxies they observed, while Georgakakis et al. (2001) reported CO in just 25% (H I in almost 50%). Wiklind et al. (1995) found CO emission from 55%. The Georgakakis et al. work, however, was based on a sample of interacting galaxies at different stages of evolution (the stage was determined by the optical colors according to the prescription given in Georgakakis et al. 2000), while the other three studies used an *IRAS* criterion that the 100 μm flux S_{100} had to be >1 Jy. Wiklind et al. (1995) carefully assessed the morphology of each galaxy in their sample, and when they removed the merger candidates the detection rate (of presumably normal ellipticals) dropped to about 40%.

What is clear, and has been since Faber & Gallagher (1976), is that gas from evolved stars *must* be returned to the interstellar medium of a galaxy, where after a Hubble time it will (if not recycled back into stars or ejected in galactic winds) account for up to ~10% of the visible mass (i.e., Ciotti et al. 1991; Kennicutt et al. 1994; Brighenti & Mathews 1997). It is also clear that new gas can be acquired by merging with like-sized galaxies, absorbing dwarf companions, or accreting pristine material from the nearby intergalactic medium.

Simple physical arguments show that the mixing of returned gas within a galaxy dominated by random motions will heat that gas to temperatures of 10^6–10^7 K, which explains why ellipticals with $L_B \geq 3 \times 10^{10}\, L_\odot$ have hot X-ray emitting halos (O'Sullivan et al. 2001). Continuing energy input from aging stars (supernovae, novae, and winds from very massive stars) keeps at least a portion of that gas hot, and may even blow it out of the galaxy. The details of energy transfer to the ISM, however, are complex and the general outcome correspondingly uncertain (cf. Mathews 1990). Simulations show that significant amounts of gas can cool near the centers (e.g., Brighenti & Mathews 1997; Pellegrini & Ciotti 1998).

Efforts to follow the evolution of the hot ISM in elliptical galaxies have led to the strong prediction that only massive galaxies will develop central reservoirs of cool gas. It is an ongoing puzzle, therefore, that observers have reported higher H I and CO detection rates among less luminous galaxies (Lake & Schommer 1984, Lees et al. 1991 for H I and CO, respectively). Lees et al. point to a possible bias against detecting broad, faint emission lines in massive objects. Another possibility is that ISM reheating by a central AGN is more effective in massive galaxies; for example, di Matteo et al. (2005) found in simulations that when the mass of the central black hole exceeds $\sim 10^7\, M_\odot$, the outflows generated can turn off star formation.

A variety of mechanisms, such as ram pressure stripping, galaxy-galaxy interactions, and perhaps thermal interactions with the hot gas or sputtering and grain destruction, affect the ISM of galaxies moving within a cluster; field galaxies should be free of such complications, and are therefore the obvious starting points for understanding internal processes governing ISM evolution. Published studies, however, have been biased not only toward cluster membership but also in favor of objects likely to contain a detectable ISM (e.g., far-infrared detection, optical dust features). Following the philosophy of our recent study of S0 galaxies (Welch & Sage 2003), we have defined a volume-limited sample of non-cluster elliptical galaxies with the aim to determine systematically their cool gas contents. We used integration times designed to reveal (at the 5 σ level) just 1% of the mass expected to be returned by stellar evolution (Ciotti et al. 1991), so that even nondetections give us physically meaningful constraints. We also take advantage of increased bandwidth compared to earlier surveys, which facilitates detection of rotationally broadened lines. This paper reports our first results: CO observations of 18 galaxies, of which we have detected emission (in either the 2−1 or 1−0 lines) from 6.

2. OBSERVATIONS AND DATA REDUCTION

We used the Nearby Galaxies Catalog (Tully 1988) to define a volume-limited sample of galaxies, with distance $d < 25$ Mpc, and declination $>-20°$, excluding members of the Virgo and Fornax Clusters. We added from the Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991, hereafter RC3) any ellipticals satisfying the same distance and declination criteria that were not in the Nearby Galaxies Catalog, arriving at a final list of 46 galaxies. Some galaxies classified as elliptical (Type 5) in the Nearby Galaxies Catalog are assigned type S0 in the RC3 (Table 1). The present sample, then, is chosen with basically the same criteria as in our recent work on lenticulars (Welch & Sage 2003; Sage & Welch 2006) with one exception: in the S0 study we excluded cases where interaction was obvious on the Palomar Sky Survey prints, and in the present case we have retained them. The galaxies thereby retained are NGC 3226, NGC 3640, and NGC 7464; we have not yet observed these objects. The entire sample is listed in Table 1. All positions and systemic velocities are from the NASA Extragalactic Database.[1]

The data were obtained through pooled (service) observations (2004 October 27 to November 8) and during a run from 2005 May 10 to May 13 (L. J. S. and G. A. W. present), at the IRAM 30 m telescope in Spain. All data reduction was done using CLASS. The observed galaxies, along with CO integrated line intensities, uncertainties and line windows, are listed in Table 2.

The data were co-added and reduced in the normal way, with a few obviously bad scans omitted. The only exception was Maffei 1, which is both large and affected by local (Milky Way) emission. We observed 5 points in Maffei 1, the center and 12″ away on either side of both the major and minor axes. Using the data from the survey of Milky Way emission (Heyer et al. 1998) we identified the contamination at all positions and removed it. No residual emission was evident in any of the scans, so we co-added all positions. There was still no evidence for any emission.

3. RESULTS

Of the galaxies observed (see Fig. 1), we detected (at the $\geq 3\ \sigma$ level) six in the 1−0 line, and three in the 2−1 line. There were no 2−1 data for Maffei 1 and NGC 7468 because a cable was unplugged during the service observing.

Unlike our survey of lenticulars, the detection rate is rather low even though integration times were designed to detect as little as 1% of the expected gas mass. Furthermore, the 2−1 line is much more difficult to see. There were several cases in the lenticular study where only the 2−1 line was seen, from which we concluded that the gas was very centrally concentrated (Welch & Sage 2003). For the elliptical galaxies the reverse seems to be true; the gas does not seem to be particularly concentrated, based on the limited line information, or it is much colder than in lenticulars. The reasoning goes as follows: if the gas is spread over a region the size of the 1−0 beam (or larger), and not unusually warm, then the 1−0 line will appear stronger than the 2−1, simply because more molecules are contributing to the emission. The lack of concentration is evident in interferometric maps (Young 2002, 2005), where of the seven galaxies studied the only CO one had a CO-emitting region smaller than the 1−0 beam at the 30 m telescope.

Elliptical galaxies are known to be generally more difficult to detect in CO emission than S0s (e.g., Lees et al. 1991). We find CO in 78% of our volume-limited S0 sample but in only 33% of the present, preliminary elliptical sample. The two samples span similar ranges of luminosity and local galaxy density. On the other hand, our observations so far have been weighted toward the more massive galaxies (we have observed 58% of targets brighter than $M(B) = -20$ but only 32% of the fainter ones), while it is known that less massive ellipticals are more likely to contain gas (i.e., Lake & Schommer 1984; Lees et al. 1991)

Table 3 contains the 2−1/1−0 line ratios for the three galaxies for which we have $>3\ \sigma$ detections in both lines. The number is too small, and the scatter too large, for us to be able to conclude anything from those ratios.

We have found published CO observations for 6 galaxies listed in Table 2: NGC 720 and NGC 4636 (Braine et al. 1997), NGC 2768 and NGC 7468 (Wiklind et al. 1995), NGC 4697 (Knapp & Rupen 1996), and NGC 4742 (Lees et al. 1991). Our results are in reasonably good agreement, although we typically report somewhat lower integrated intensities or more sensitive upper limits.

4. CO DETECTION RATES IN E AND S0 GALAXIES

The striking difference in CO detection rates between ellipticals and lenticulars may offer important guidance for future investigations of ISM evolution in early type galaxies. We have speculated (Sage & Welch 2006) that the CO emission from S0 galaxies comes mainly from gas that has cooled out of the hot, X-ray phase, i.e., gas returned by the stars. It is not yet evident that the same is true in elliptical galaxies (one of our goals is to address this issue with more data). Monolithic models of ISM evolution in early type galaxies incorporate a variety of factors, which influence whether, and how much, gas cools from the hot phase (e.g., Mathews 1990; Ciotti et al. 1991; Brighenti & Mathews 1997; Pellegrini & Ciotti 1998); those include the mass of the dark halo, the effectiveness of (Type Ia) supernova heating, and active galactic nucleus (AGN) feedback.

More massive dark matter halos promote the cooling of gas near the center by inhibiting the development of a galactic wind; since more hot gas is retained globally, however, the X-ray luminosities are also higher. Models with high $L(X)$ might therefore also develop central clouds of atomic and/or molecular gas (but those models, e.g., Ciotti et al. [1991], do not follow the detailed evolution of the cold ISM). In general, ellipticals are found to have higher X-ray luminosities and larger $L(X)/L(B)$ than lenticulars (Eskridge et al. 1995a, 1995b), consistent with them being more dark matter dominated. If the cold gas in both galaxy

[1] The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

TABLE 1

Properties of Galaxies in the Volume-limited Sample

Name	R.A. J2000.0	Decl. J2000.0	v_{hel} (km s^{-1})	Type	Distance (Mpc)	$B^0{}_T$
NGC 584	01 31 20 7	−06 52 05	1802	E4	23.4	−20.68
NGC 596	01 31 36 8	−06 53 37	1876	E+pec (unc)	23.8	−20.22
NGC 636	01 39 06 5	−07 30 45	1860	E3	24.2	−19.71
NGC 720	01 53 00 5	−13 44 19	1745	E5	20.3	−20.38
NGC 821	02 08 21 1	+10 59 42	1735	E6 (doubtful)	23.2	−20.21
NGC 855	02 14 03 6	+27 52 38	595	E	4.3	−15.28
IC 225	02 23 53 8	+01 09 38	1535	E	17.0	−16.72
Maffei 1	02 36 35 4	+59 39 19	13	gE	3.6	−20.50
NGC 1052	02 41 04 8	−08 15 21	1510	E4	17.8	−19.81
NGC 1172	03 01 36 0	−14 50 12	1669	E+ (unc)	18.3	−18.50
NGC 1297	03 19 14 2	−19 06 00	1578	SAB0 (pec)	18.3	−18.71
Haro 20/UGCA 073	03 28 14 5	−17 25 10	1866	E+ (doubtful)	21.9	−16.94
NGC 1407	03 40 11 9	−18 34 49	1779	E0	21.6	−21.02
NGC 2768	09 11 37 5	+60 02 14	1373	E6 (unc)	23.7	−21.13
NGC 3073	10 00 52 1	+55 37 08	1155	SAB0−	19.3	−18.03
N3115 DW1	10 05 41 6	−07 58 53.4	698	"dE1,N"	13.4	−17.07
NGC 3156	10 12 41 2	+03 07 46	1318	S0 (unc)	18.6	−18.54
NGC 3193	10 18 24 9	+21 53 55	1399	E2	23.2	−20.05
NGC 3226	10 23 27 0	+19 53 55	1151	E3 pec (unc)	23.4	−19.57
NGC 3377	10 47 49 6	+13 59 08	665	E5+	8.1	−18.55
NGC 3379	10 47 49 6	+12 34 54	911	E1	8.1	−19.39
UGC 5955	10 52 04 2	+71 46 23	1249	E	16.8	−17.12
NGC 3522	11 06 40 4	+20 05 08	1221	E	20.6	−17.46
IC 678	11 14 06 4	+06 34 37	968	E	17.6	−16.48
NGC 3605	11 16 46 6	+18 01 02	668	E4	16.8	−18.03
NGC 3608	11 16 58 9	+18 08 55	1253	E2	23.4	−19.94
NGC 3640	11 21 06 8	+03 14 05	1251	E3	24.2	−20.78
NGC 3818	11 41 57 3	−06 09 20	1701	E5	24.7	−19.52
NGC 4033	12 00 34 7	−17 50 33	1617	E6	23.9	−19.49
NGC 4125	12 08 06 0	+65 10 27	1356	E6 pec	24.2	−21.35
NGC 4239	12 17 14 9	+16 31 53	940	E	16.6	−18.09
UGC 7354	12 19 09 9	+03 51 21	1526	E pec (unc)	14.6	−16.52
NGC 4278	12 20 06 8	+29 16 51	649	E1+	9.7	−18.82
NGC 4283	12 20 20 8	+29 18 39	984	E0	9.7	−17.02
NGC 4308	12 21 56 9	+30 04 27	589	E (unc)	9.7	−15.83
NGC 4494	12 31 24 0	+25 46 30	1344	E1+	9.7	−19.23
UGC 7767	12 35 32 4	+73 40 29	1282	E	17.9	−17.73
NGC 4648	12 41 44 4	+74 25 15	1414	E3	20.4	−18.84
NGC 4627	12 41 59 7	+32 34 25	542	E4 pec	13.7	−17.71
NGC 4636	12 42 49 9	+02 41 16	938	E0+	17.0	−20.68
UGCA 298	12 46 55 4	+26 33 51	801	E+ (unc)	8.9	−15.14
NGC 4697	12 48 35 9	−05 48 03	1241	E6	23.3	−21.67
NGC 4742	12 51 48 0	−10 27 17	1270	E4 (unc)	23.2	−19.81
NGC 5845	15 06 00 8	+01 38 02	1450	E (unc)	21.9	−18.16
NGC 7464	23 01 53 7	+15 58 26	1875	E1 pec (unc)	19.2	−17.39
NGC 7468	23 02 59 2	+16 36 19	2081	E3 pec (unc)	23.2	−18.03

Notes.—Columns list galaxy name, coordinates at epoch J2000.0, heliocentric radial velocity, morphological type from the Third Reference Catalog of Bright Galaxies (RC3), distance in Mpc, either from the Tully Catalog or, when unavailable, from V_{3K} in the RC3 with $H_0 = 75$ km s^{-1} Mpc^{-1}, total corrected blue apparent magnitude from the RC3. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

types primarily originates in cooling from a hot phase, one might therefore expect higher CO detection rates in our elliptical sample, which is contrary to what we find. We caution, however, that our samples of E and S0 galaxies include relatively fewer high-luminosity objects than the *Einstein* sample (with correspondingly low X-ray detection rates), and may therefore not reflect the trends found by Eskridge et al. On the other hand, Braine et al. (1997) found no CO emission from a sample of six luminous ellipticals.

AGN feedback is currently thought theoretically to be important in suppressing cooling flows in both clusters and individual elliptical galaxies (di Matteo et al. 2005; Sazonov et al. 2005), and observational evidence supporting that view has recently been reported (Schawinski et al. 2006). Although the process is complex and only partly understood (cf. Brighenti & Mathews 2002, 2003), the current picture of AGN energy production (Binney & Tabor 1995; Ciotti & Ostriker 1997; and more recently Brighenti & Mathews 2006) suggests that feedback is likely to occur, at least initially, along the spin axis of the central supermassive black hole. Since that axis would not often point toward the disk of a lenticular host galaxy, cooling gas from its disk stars might often escape being reheated, which might lead to the observed higher detection frequency in S0s. In other words, AGN reheating might

TABLE 2

Integrated Intensities

Name	Window (km s^{-1})	$I_{CO}(1-0)$ (K km s^{-1})	rms (K)	$I_{CO}(2-1)$ (K km s^{-1})	rms (K)
NGC 636	1773–1931	0.34 ± 0.23	0.0051	<0.27	0.0060
NGC 720	1543–1972	0.63 ± 0.47	0.0054	<0.46	0.0054
IC 225	1523–1594	0.21 ± 0.046	0.0016	0.16 ± 0.033	0.0012
Maffei 1	−99–166	<0.13	0.0022	...	...
NGC 1407	1478–2058	<0.58	0.0051	<0.62	0.0055
NGC 2768	1168–1571	0.67 ± 0.28	0.0035	0.92 ± 0.30	0.0038
NGC 3073	1093–1205	0.50 ± 0.083	0.0023	0.45 ± 0.083	0.0023
NGC 3115 DW1	517–901	<0.26	0.0034	<0.19	0.0025
NGC 3193	1203–1602	<0.67	0.0085	<0.87	0.011
NGC 3605	425–907	<0.41	0.0046	<0.38	0.0042
NGC 4239	768–1091	0.46 ± 0.29	0.0043	<0.34	0.0050
NGC 4283	871–1110	0.88 ± 0.21	0.0038	<0.26	0.0047
NGC 4494	1061–1541	1.44 ± 0.39	0.0044	0.87 ± 0.53	0.0060
NGC 4648	1251–1672	<0.31	0.0038	0.58 ± 0.30	0.0037
NGC 4636	794–1114	0.24 ± 0.20	0.0029	<0.13	0.0020
NGC 4697	1057–1482	<0.44	0.0052	0.75 ± 0.51	0.0060
NGC 4742	1057–1482	0.32 ± 0.21	0.0027	<0.23	0.0029
NGC 7468	1966–2319	1.06 ± 0.23	0.0032	...	...

Notes.—Columns list the galaxy name, location of line window, and for both CO lines the integrated line intensity in the line window and its formal standard deviation along with rms channel noise in the smoothed spectrum. All upper limits are 1 σ, and they are used whenever the formal line intensity is less than 1 σ. For two galaxies, Maffei 1 and NGC 7468, no 2−1 data were obtained because a cable was unplugged during the pooled observations. For Maffei 1, we observed 5 positions, center, and 12″ away along both the major an minor axes. No emission was evident at any position. The result above contains data from all positions co-added, with the local Milky Way emission removed.

be more effective in a pure spheroid simply because gas return is more isotropic than in a disk galaxy. Published simulations, however, have not yet featured directed AGN feedback within disks, so that explanation remains speculative. Sazonov et al. (2005) did show that when the mass of gas drops below 1% of the mass of stars in the central region, radiative heating by the AGN overwhelms cooling, and much of the remaining gas will be expelled.

The flattened shapes of lenticulars are expected to make it easier for supernovae to heat and eject returned gas (cf. D'Ercole & Ciotti 1998). While that might help explain the generally lower X-ray luminosities among S0 galaxies, it would also seem to predict lower, not higher, CO detection rates among S0s, contrary to the observations.

In the hierarchical formation picture lenticular and elliptical galaxies are products of different merging histories. We have already commented on our current, blurry picture of elliptical galaxy formation. Even less obvious is the way to make lenticular galaxies in low-density environments (Stocke et al. 2004), although it seems that most S0s cannot simply be former spirals (Burstein et al. 2005). Furthermore, it remains to be worked out how differing assembly sequences for Es and S0s can account for differences in cold gas detection rates, in the distribution of the molecular and atomic phases, and possibly also in the global values of $M(H_2)/M(\mathrm{H\,I})$ (see below); at present there is much room for speculation. For example, perhaps ellipticals typically form in somewhat dryer mergers than lenticulars, as larger gas contents do seem to produce diskier remnants. Barnes (2002) showed that, depending on merger geometry, some tens of percent of the gas carried into a major merger could end up in a large-scale gas disk that could later form a stellar disk. Naab et al.(2006a) also showed that the presence of even small amounts of gas in a merger tends to make the remnant more axisymmetric, more dominated by minor axis tube orbits, and less boxy (and so more like a lenticular galaxy). On the other hand, perhaps timing is important, in that ellipticals usually acquired their gas earlier than S0s, and have had more time to dispose of it by feeding an AGN and/or making stars.

Previous surveys have reported higher cool gas detection rates among low-luminosity E and S0 galaxies (Lake & Schommer [1984] and Lees et al. [1991] for H I and CO, respectively); our results show a similar trend, albeit from small numbers. We find CO in only 1 of 7 galaxies (or 14%) brighter than $M(B) = -20$, but in 5 of 11 (45%) of fainter galaxies. For a cut at $M(B) = -19$ the results are 20% and 50%, respectively. The lower CO content in the more massive galaxies may arise because the high-luminosity galaxies are more likely formed in dry mergers (Bell et al. 2006; Boylan-Kolchin et al. 2006), or perhaps the evolution of the gas is dominated by AGN feedback (Sazonov et al. 2005). In contrast, other published simulations of ISM evolution inside isolated galaxies (e.g., Ciotti et al. 1991; Pellegrini & Ciotti 1998) suggest that cool gas more readily accumulates in brighter, not fainter, ellipticals.

In summary, the detection rates of molecular gas among early-type galaxies are not easy to understand from their other properties, and useful predictions are not available from either of the two competing paradigms of galaxy formation. Much more work is needed to bring a consensus into view.

5. COOL GAS IN THE VOLUME LIMITED SAMPLE: A FIRST LOOK

One of the most puzzling and, we believe, potentially most significant discoveries from our survey of S0 galaxies has been the existence of a cutoff in the amount of cool gas present (Sage & Welch 2006). Regardless of luminosity, the most gas-rich lenticulars have $\sim$10% of the amount returned by their stars after the first 0.5 Gyr. Table 4 presents the H_2 and H I masses for ellipticals from our work and the literature, respectively. Although we have both CO and H I data for less than half of the elliptical sample (lack of CO observations is the main deficiency), there is already an indication that the same cutoff may be present (Fig. 2). The

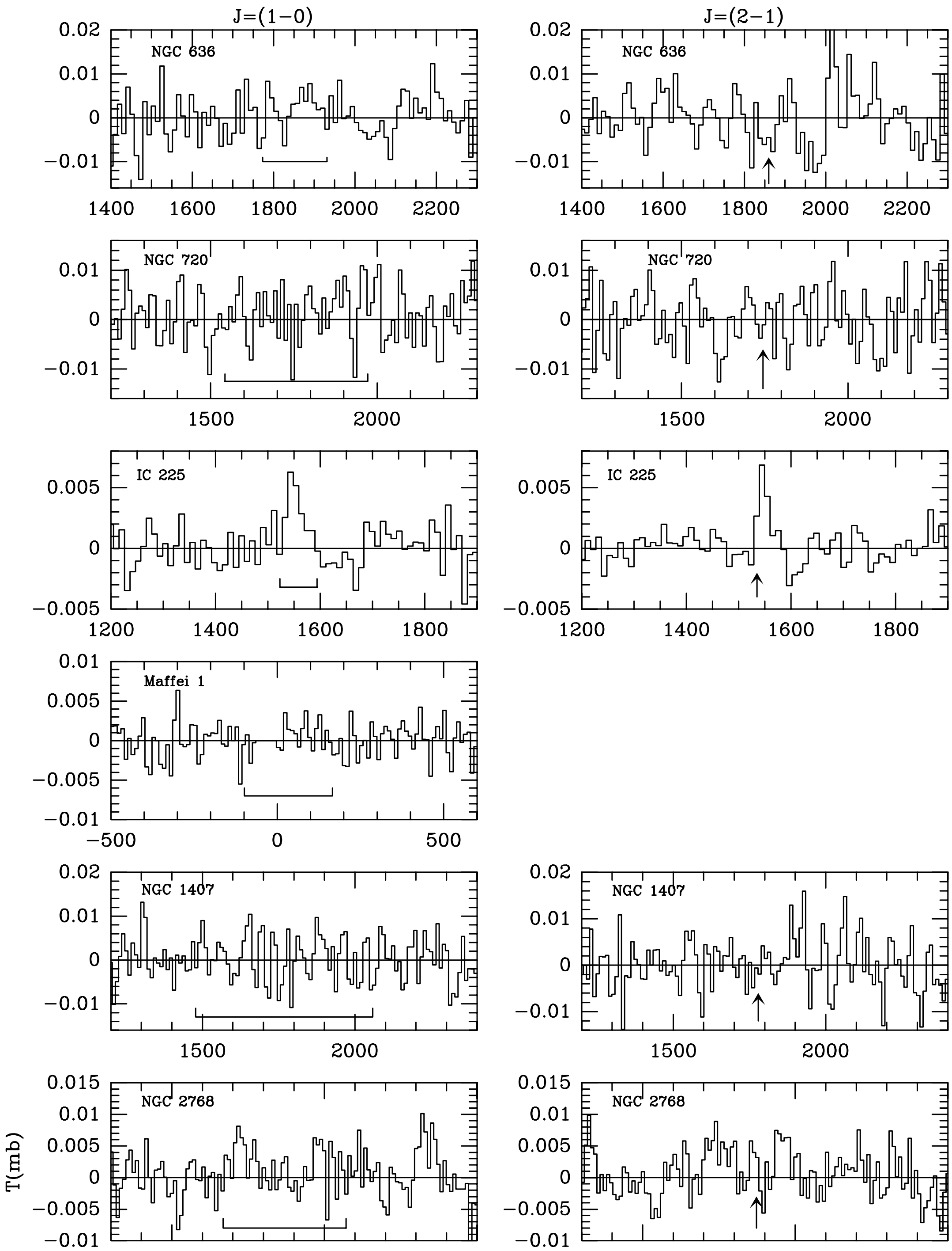

FIG. 1.—CO spectra from the IRAM 30 m telescope. The arrow in the $J = 2 - 1$ column indicates the optical systemic velocity from NED. The solid line in the $J = 1 - 0$ column shows the velocity range over which the integrated line intensity was calculated.

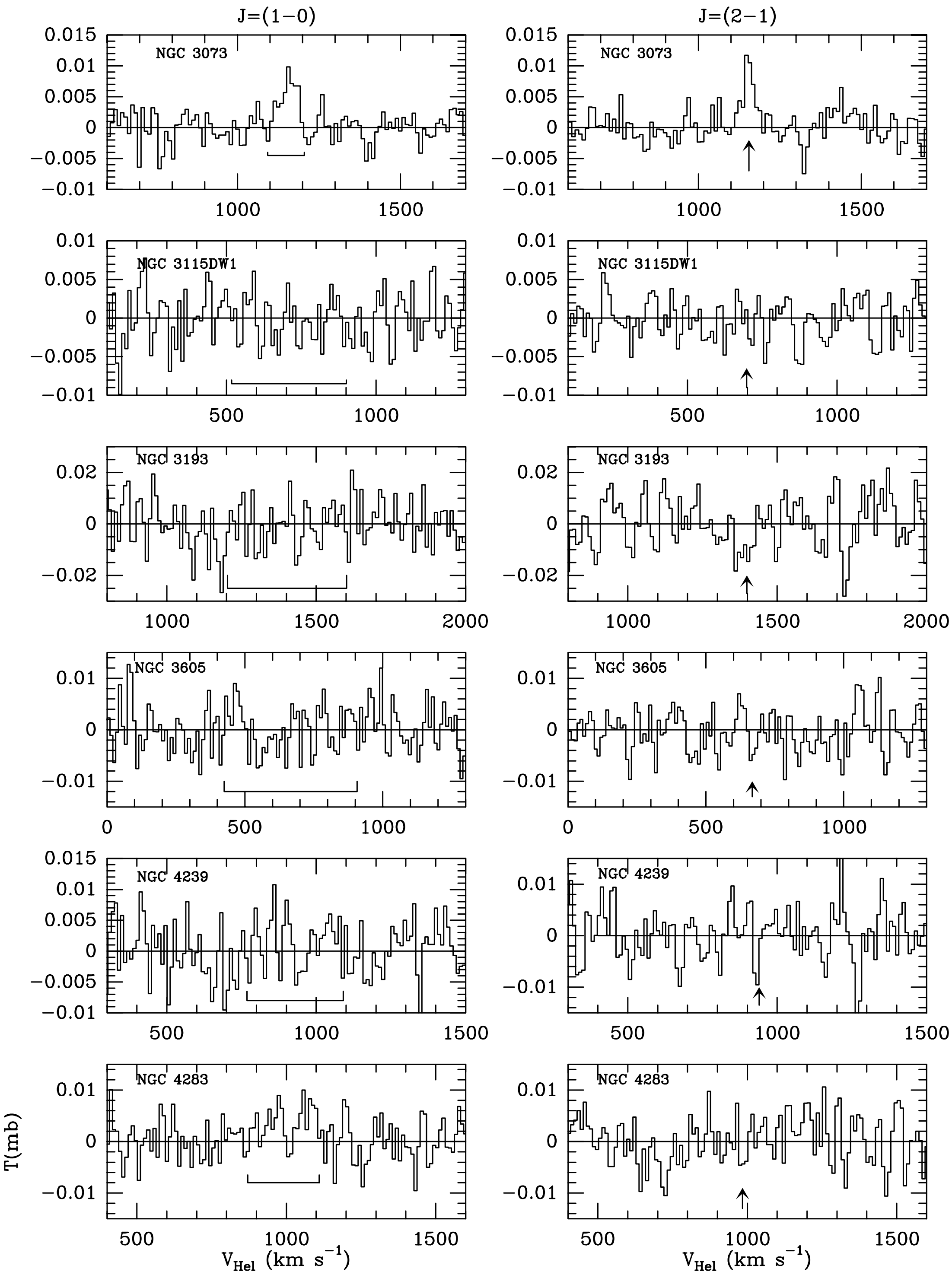

FIG. 1—*Continued*

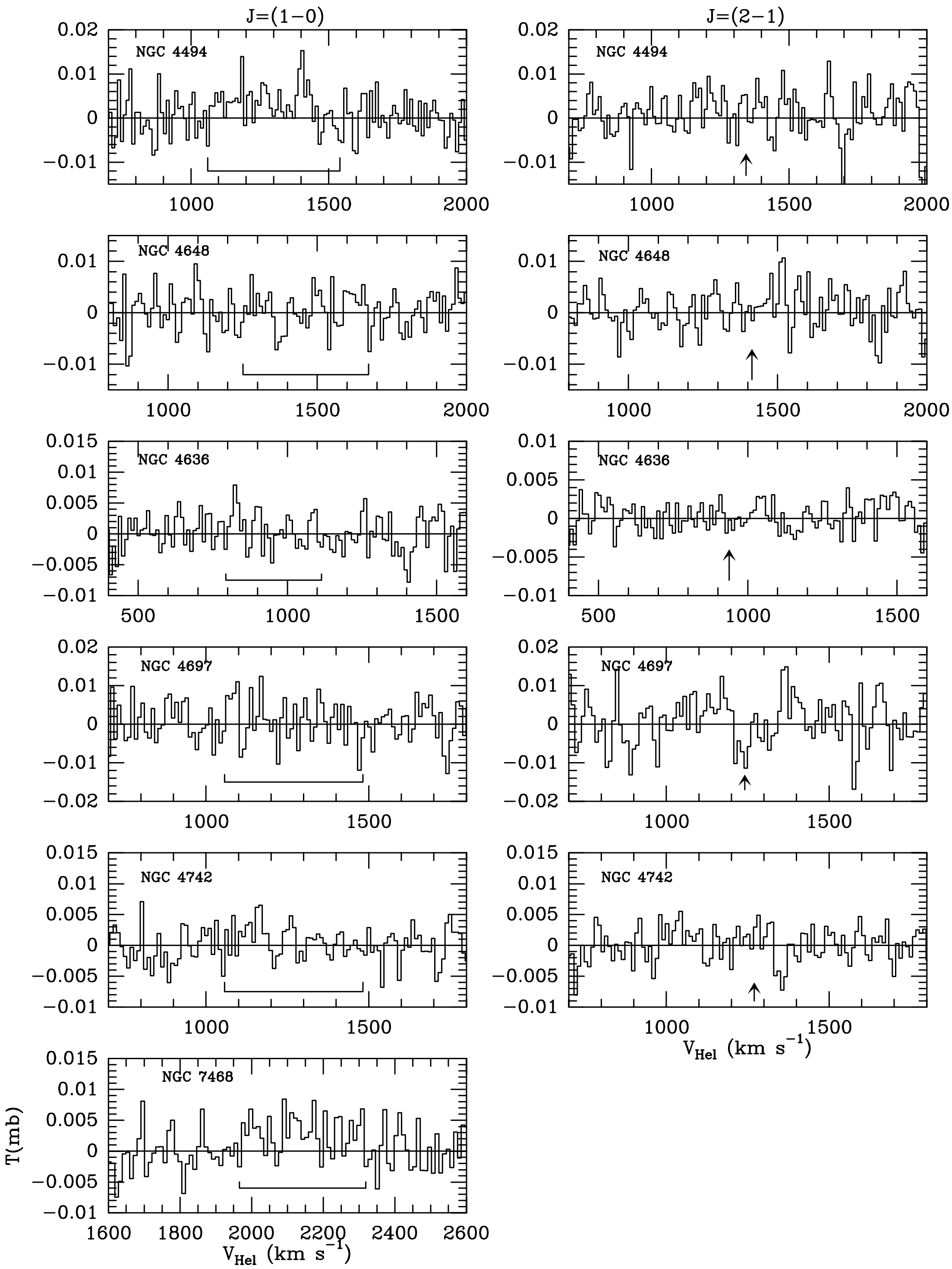

FIG. 1—*Continued*

TABLE 3
2−1/1−0 LINE RATIOS

Name	$I_{CO}(2-1)/I_{CO}(1-0)$
IC 225	0.76 ± 0.06
NGC 2768	1.4 ± 0.4
NGC 3073	0.9 ± 0.1

NOTE.—For the three galaxies with >3 σ detections in both lines we have calculated the line ratios (with all the usual caveats about differing beam sizes).

outstanding exception is NGC 7468 (Markarian 314), which has almost as much gas as predicted by Ciotti et al. (1991); most of this is H I. Although isolated, its optical structure is clearly peculiar. Perhaps NGC 7468 has recently acquired additional atomic gas from nearby.

The cool gas in ellipticals and S0s may have another common attribute: galaxies with the most gas also have relatively more in the atomic phase. The correlation, shown in Figure 3, is merely suggestive due to the paucity of observations; the reader should compare with the analogous plot for S0 galaxies in Figure 13 in Sage & Welch (2006). An interesting difference between the two plots is their relative offset in $M(H_2)/M(\text{H I})$: elliptical galaxies seem more deficient in molecular gas than S0s by an order of magnitude, when compared at the same value of $M(\text{ISM})/M(\text{PRE})$. If cooling flows generate most of the observed molecular gas in early-type galaxies, that result would suggest that some mechanism, perhaps AGN reheating, moderates them more effectively in ellipticals.

In summary, we have begun to assess the amount of cool gas within the members of a volume-limited sample of elliptical galaxies. CO is much more frequently detected in S0s, which we speculate might be because AGN feedback is less effective at reheating the gas returned within disks. Currently available data indicate that whatever mechanisms operate to impose a cutoff on the cool gas mass in S0 galaxies also operate in ellipticals. A clear but still poorly established trend that more gas rich ellipticals have relatively more atomic gas mimics the more robust trend shown by S0s. We emphasize that additional CO observations (and in some cases H I observations) are needed to improve the statistics, because of our small sample size. Differences in the gas properties of ellipticals and lenticulars may reveal robust new indications of whether their formation mechanisms differed and how their evolution proceeded. We are not yet able to identify the physical causes of the trends we report. More realistic simulations of ISM evolution, based on each of the competing paradigms of galaxy evolution, monolithic and hierarchical, will be needed to accomplish that.

TABLE 4
TOTAL COOL GAS MASSES

Name	$M(H_2)$ ($M_\odot$)	M(H I) ($M_\odot$)	H I reference
NGC 636	$<1.67 \times 10^7$	1.66×10^8	1
NGC 720	$<2.40 \times 10^7$	$<2.58 \times 10^8$	1
IC 225	2.50×10^6		
Maffei 1	$<2.08 \times 10^5$		
NGC 1407	$<3.35 \times 10^7$	$<9.79 \times 10^8$	1
NGC 2768	1.55×10^7	1.98×10^8	2
NGC 3073	7.68×10^6	1.66×10^8	3
NGC 3115 DW 1	$<5.78 \times 10^6$		
NGC 3193	$<4.46 \times 10^7$	$<7.98 \times 10^7$	4
NGC 3605	$<1.43 \times 10^7$	$<2.39 \times 10^7$	5
NGC 4239	$<9.89 \times 10^6$	$<9.12 \times 10^6$	6
NGC 4283	3.41×10^6	4.15×10^7	1
NGC 4494	5.59×10^6	$<9.96 \times 10^6$	7
NGC 4648	$<1.60 \times 10^7$	$<1.76 \times 10^7$	8
NGC 4636	$<7.15 \times 10^6$	$<6.12 \times 10^7$	9
NGC 4697	$<2.96 \times 10^7$	$<1.84 \times 10^9$	10
NGC 4742	$<1.40 \times 10^7$	$<4.22 \times 10^8$	1
NGC 7468	2.35×10^7	1.59×10^9	2

NOTES.—Columns contain galaxy name, H_2 mass or upper limit from this work, H I mass or upper limit, source of H I estimate. A CO-to-H_2 conversion factor of 2.3×10^{20} mol cm^{-2} (K km s^{-1}) has been used. We cannot find H I observations for 3 galaxies. Upper limits are 3 σ.

REFERENCES.—(1) Huchtmeier 1994; (2) Huchtmeier et al. 1995; (3) Irwin et al. 1987; (4) Williams et al. 1991; (5) Knapp et al. 1979; (6) Lake & Schommer 1984; (7) Bregman et al. 1992; (8) Richter & Huchtmeier 1987; (9) Kumar &Thonnard 1983; (10) Gallagher et al. 1975.

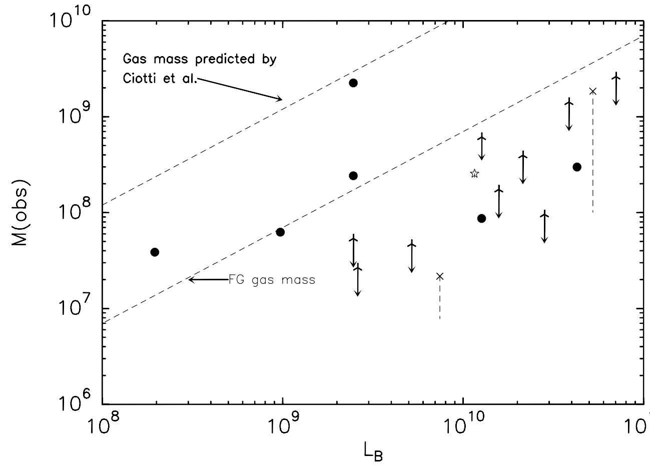

FIG. 2.—Observed gas mass as a function of blue luminosity, compared to the mass predicted to be returned by evolving stars (*lines*). Filled circles are derived from sums of measured H I and H_2 masses. Measurements of $M(H_2)$ added to 3 σ upper limits on M(H I) are shown as by a cross, with dashed lines extending down to the value of $M(H_2)$. The star indicates an analogous treatment of a measurement of M(H I) and a 3 σ limit on $M(H_2)$. Three-armed crosses with downward arrows mark the sums of two 3 σ mass limits. All values are scaled by a factor of 1.4 to account for Helium.

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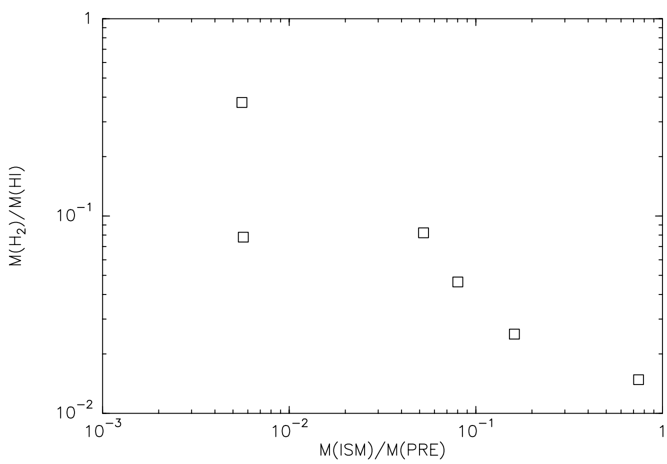

FIG. 3.—Ratio of molecular to atomic gas mass as a function of the mass fraction, i.e., the ratio of the total observed mass of cool gas to the mass predicted by the Ciotti et al. (1991) analytical approximation; compare to Fig. 13 in Sage & Welch (2006) for S0 galaxies.

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