THE ASTROPHYSICAL JOURNAL, 301:L13–L17, 1986 February 1


# CO IN H I–DEFICIENT VIRGO CLUSTER SPIRAL GALAXIES

JEFFREY D. KENNEY AND JUDITH S. YOUNG
Department of Physics and Astronomy, University of Massachusetts at Amherst;
and Five College Radio Astronomy Observatory
*Received 1985 August 27; accepted 1985 November 20*

## ABSTRACT

We have mapped CO emission along the major axis of 23 Virgo cluster spiral galaxies, including many of the H I–deficient spirals. These galaxies appear to have roughly normal CO luminosities and extents, relative to optical properties. The existence of galaxies with unusually large ratios of molecular gas to atomic gas indicate that some process has removed the low-density atomic gas and left the denser molecular gas relatively unscathed. This conclusion is supported by the observation that the ratio of CO to H I diameters decreases away from M87. These results are consistent with a process which selectively strips low-density material, such as ram pressure stripping, thermal evaporation, or turbulent viscous stripping. The relatively large fraction of H I–deficient spirals in Virgo suggests that gas removal events have taken place over at least a cluster crossing time, or $\sim 10^9$ yr. If atomic gas is removed from the inner disk, the fact that the molecular gas has not yet responded to the atomic gas removal indicates that the molecular phase in galaxies is long-lived.

*Subject headings:* galaxies: general — interstellar: molecules — stars: formation

Although it is well known that stars form in molecular clouds, there is little known about the relationship between the atomic and molecular phases of the interstellar medium (ISM) in the star formation history of galaxies. The Virgo cluster environment, however, is apparently altering the atomic gas content of its galaxies (e.g., Giovanelli and Haynes 1983), with a resultant change in the star formation properties of its member galaxies (Kennicutt 1983). Virgo, therefore, serves as a laboratory to study the cycling of gas between the atomic and molecular phases, and the role of each in star formation.

Evidence has been accumulating over the last decade that the atomic gas content of many Virgo spirals is low by factors ranging from 2 to 10, compared with more isolated spirals of the same type and optical size (see review by Haynes, Giovanelli, and Chincarini 1984). Ablation caused by the interaction of the galaxies' ISM with the intracluster gas is the currently favored explanation for the H I deficiency. Mapping of the H I emission in Virgo spirals (Giovanelli and Haynes 1983; van Gorkom and Kotanyi 1985; Warmels 1985) shows that the H I radial extent is reduced in the H I–deficient systems, indicating that ablation occurs predominantly in the outer parts of the disk.

With the goal of determining whether molecular gas is also deficient in the H I–deficient Virgo spirals, we have mapped CO in 23 Virgo galaxies. These galaxies are a subset of the complete, magnitude-limited, H I sample of Helou, Hoffman, and Salpeter (1984). The sample presented here includes primarily the brighter galaxies in the Helou sample, with a wide range of galaxy type, cluster position, and H I deficiency. Observations were made in 1984 and 1985 with the 14 m telescope of the Five College Radio Astronomy Observatory. At the 115.271 GHz frequency of the CO $J = 1 \rightarrow 0$ emission line, the telescope has a half-power beamwidth of 45″. Position-switched spectra were taken every 45″ along the major axis of each galaxy, out to where no emission could be detected in 2 hr. Typically, 3–9 positions were observed.

The total CO luminosity for a galaxy can then be estimated by assuming that the emission is azimuthally symmetric in the disk. From observations of more nearby galaxies, we deduce that the assumption of azimuthal symmetry results in an uncertainty in the total CO luminosity of $\sim 20\%$. The mass of $H_2$ is assumed to be directly proportional to the CO luminosity, on the basis of the empirical relation of Young and Scoville (1982) between CO integrated intensity and $H_2$ surface density in the Galaxy. Theoretically, CO is expected to be a good tracer of the $H_2$ mass for molecular clouds which are virialized (Dickman, Snell, and Schloerb 1986). Possible variations in the gas temperature or metallicity among galaxies may add to the scatter in the relationships which will be discussed, but will not otherwise affect the conclusions in this *Letter*. Table 1 lists the CO luminosities, $H_2$ masses, and other parameters for the Virgo sample. Figure 1 (Plate L6) displays CO spatial-velocity maps for three of the Sc galaxies. A complete presentation and description of the data is in preparation.

To assess the molecular gas normalcy of Virgo spirals, we first compare both the atomic and molecular gas masses normalized to the total blue stellar luminosity for the 14 Sbc–Scd galaxies in the Virgo sample with a comparison sample of 11 non-Virgo galaxies of the same type. In this section we concentrate on the late-type spirals, since more CO data on non-Virgo Sc's exists; the results for the early-type spirals appear to be the same. Galaxies in the comparison sample are taken from the nearby and infrared-selected galaxies of similar size already mapped with similar sensitivity at FCRAO. Because of the selection criteria, and the fact that some of the members of the comparison sample are in groups, this sample does not constitute an ideal control sample. The

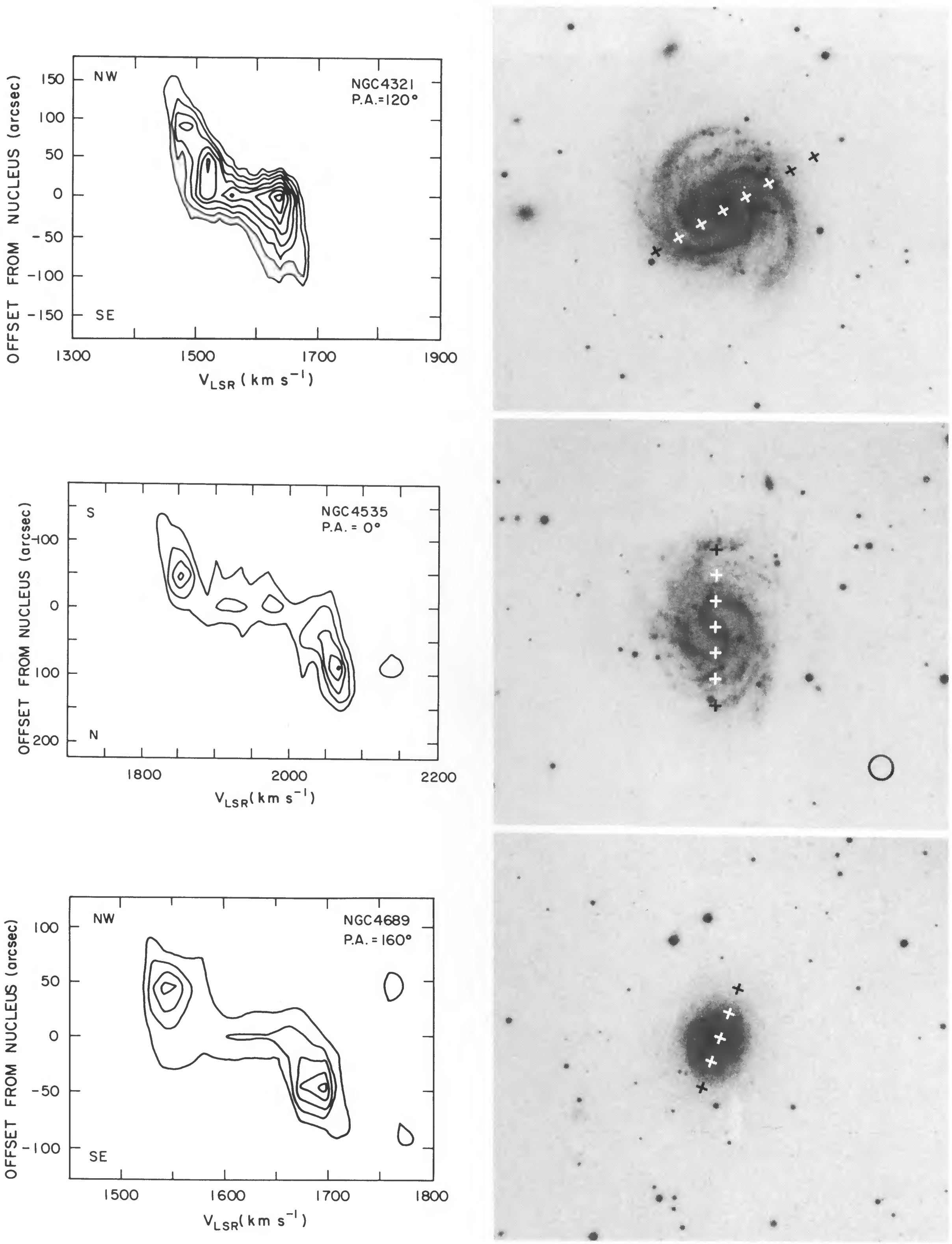


FIG. 1.—CO spatial-velocity maps and Palomar Sky Survey photographs of three of the Sc galaxies in the Virgo sample. NGC 4535 has normal H I emission, while NGC 4321 is deficient by a factor of 3, and NGC 4689 is deficient by a factor of 10. The contour increment in each spatial-velocity map is 14 mK ($T_R^*$). The lowest contour is 28 mK in NGC 4321, and 14 mK in NGC 4535 and NGC 4689. X's on photos indicate positions where data were taken; circle indicates beam size (HPBW).

KENNEY AND YOUNG (*see* page L13)

TABLE 1

VIRGO GALAXY PROPERTIES

| Galaxy NGC Number | Type[a] | $R_{M87}$[b] (°) | $B_T^o$[c] | $L_B$[d] ($10^9 L_\odot$) | $L_{CO}$[e] (K km s$^{-1}$ kpc$^2$) | $M_{H_2}$[f] ($10^8 M_\odot$) | $M_{H\,I}$[g] ($10^8 M_\odot$) | H I Deficiency[h] |
|---|---|---|---|---|---|---|---|---|
| 4178...... | SBc(s)II | 4.7 | 11.35 | 18 | ≤ 140 | ≤ 8.6 | 63 | −0.13 |
| 4192...... | SbII: | 4.9 | 10.31 | 47 | 390 | 24 | 79 | 0.09 |
| 4212...... | Sc(s)II–III | 3.9 | 11.52 | 15 | 220 | 13 | 11 | 0.44 |
| 4254...... | Sc(s)I.3 | 3.6 | 10.13 | 55 | 1880 | 113 | 68 | 0.02 |
| 4303...... | Sc(s)I.2 | 8.0 | 9.95 | 65 | 1330 | 80 | 94 | 0.17 |
| 4321...... | Sc(s)I | 4.0 | 9.89 | 69 | 1820 | 109 | 36 | 0.52 |
| 4388...... | Sab | 1.3 | 11.20 | 21 | 80 | 4.8 | 5.0 | 1.06 |
| 4394...... | SBb(sr)I–II | 5.9 | 11.47 | 16 | 130 | 7.6 | 4.4 | 0.85 |
| 4402...... | Sc(edge) | 1.4 | 12.01 | 10 | 180 | 11 | 6.8 | 0.61 |
| 4438...... | Sb(tides) | 1.0 | 10.43 | 42 | 80 | 4.8 | 5.2 | 1.28 |
| 4450...... | Sab pec | 4.7 | 10.63 | 35 | 190 | 12 | 4.2 | 1.31 |
| 4501...... | Sbc(s)II | 2.1 | 9.85 | 72 | 1140 | 68 | 29 | 0.47 |
| 4535...... | SBc(s)I.3 | 4.3 | 10.22 | 51 | 870 | 52 | 81 | 0.17 |
| 4548...... | SBb(rs)I–II | 2.4 | 10.72 | 32 | 400 | 24 | 10 | 0.86 |
| 4567[i] .... | Sc(s)II–III | 1.8 | 11.78 | 12 | 230 | 14 | 20[i] | 0.64[i] |
| 4568[i] .... | Sc(s)III | 1.8 | 11.27 | 19 | 450 | 27 | | |
| 4569...... | Sab(s)I–II | 1.7 | 9.86 | 71 | 730 | 44 | 12 | 0.99 |
| 4571...... | Sc(s)II–III | 2.4 | 11.63 | 14 | 180 | 11 | 14 | 0.44 |
| 4579...... | Sab(s)II | 1.8 | 10.31 | 47 | 450 | 27 | 11 | 1.00 |
| 4651...... | Sc(r)I–II | 5.1 | 10.99 | 25 | 150 | 8.7 | 54 | −0.16 |
| 4654...... | SBc(rs)II | 3.3 | 10.82 | 29 | 450 | 27 | 53 | 0.00 |
| 4689...... | Sc(s)II.3 | 4.4 | 11.34 | 18 | 330 | 20 | 8.6 | 1.06 |
| 4713...... | SBc(s)II–III | 8.5 | 11.83 | 12 | ≤ 90 | ≤ 5.7 | 55 | −0.30 |

[a] Morphological types from Sandage, Binggeli, and Tammann 1985 if available; otherwise from RSA.

[b] Angular distance from M87.

[c] Blue magnitude, where $B_T$ is from de Vaucouleurs and Pence 1979; $B_T^o - B_T$ is from RC2.

[d] Blue luminosity, using $B_T(\mathrm{Sun}) = -26.09$ (Allen 1973), assuming $D = 20$ Mpc for all galaxies.

[e] CO luminosity, from $L_{CO} = \Sigma I_{CO} A \cos(i)$, where $I_{CO} = \int T_R^* \, dv$, $A$ = area of galaxy covered by beam, $i$ = inclination, from Helou *et al.* 1981 or Helou, Hoffman, and Salpeter 1984; upper limits are $2\sigma$; typical $1\ \sigma$ uncertainty ~ 30%.

[f] $H_2$ mass, from $M_{H_2}(M_\odot) = 6 \times 10^6\ L_{CO}$ (K km s$^{-1}$ kpc$^2$) (Young and Scoville 1982).

[g] H I mass, taken from Giovanelli and Haynes 1983, Helou *et al.* 1981, and Helou, Hoffman, and Salpeter 1984, in that order.

[h] H I deficiency values, taken from Giovanelli and Haynes 1985, or computed according to Giovanelli and Haynes 1983.

[i] NGC 4567 and NGC 4568 are an interacting pair; the Arecibo beam does not resolve the galaxies: the H I mass is the total for the system, the H I deficiency is an estimate of the average deficiency of the two galaxies.

two samples cover the same range of blue luminosity, although there is an excess of lower luminosity Virgo galaxies. However, eliminating these galaxies does not alter the results discussed below. The two samples have similar $L_{IR}/L_B$ distributions, so that absorption corrections to the blue luminosity do not affect the mean of the samples differently.

The histograms in Figure 2 show that the ratio $M_{H\,I}/L_B$ is low in Virgo Sc's by a factor of 2 with respect to the sample of non-Virgo Sc's, but that the ratio $M_{H_2}/L_B$ is the same in the Virgo and non-Virgo samples. The shaded regions in Figure 2 denote galaxies which have an H I deficiency greater than 0.4 (corresponding to a factor of 2.5). H I deficiency values (Giovanelli and Haynes 1983, 1985) are measured with respect to isolated galaxies of the same morphological type and optical size and are defined as (H I Def) = $\log(M_{H\,I\,\mathrm{expected}}/M_{H\,I\,\mathrm{observed}})$. The distribution of these H I-deficient Virgo galaxies in the $\log(M_{H_2}/L_b)$ plot is no different than that of the non–H I-deficient Virgo galaxies, suggesting that there is no molecular gas deficiency in the H I-deficient Virgo Sbc–Scd galaxies.

Since the above comparison relies on a CO comparison sample which is not exclusively composed of isolated galaxies, we present next a comparison which does not depend on this sample. In Figure 3 we compare the $H_2$/H I mass ratio with the H I deficiency values for the Virgo galaxies. From Figure 3, it appears that Virgo galaxies with large values of $M(H_2)/M(\mathrm{H\ I})$ are H I-deficient. Furthermore, the molecular-to-atomic gas ratio appears to depend upon morphological type and luminosity in that the most luminous Sbc–Sc galaxies all appear above and to the left of the other galaxies in Figure 3. This may indicate that more massive galaxies (disks) are more effective in turning their H I into $H_2$. If the Virgo galaxies were as deficient in $H_2$ as they are in H I, the points in this figure would lie about a line with a slope of 0. Most of the points are better described by a line with a slope of 1, which denotes a normal $H_2$ content. Shown is a line with a slope of 1, placed to roughly fit the less luminous Sbc–Scd galaxies. Two of the severely H I-deficient galaxies near the center of the cluster, NGC 4388 and NGC 4438, fall below the mean relation, and thus might be considered to be

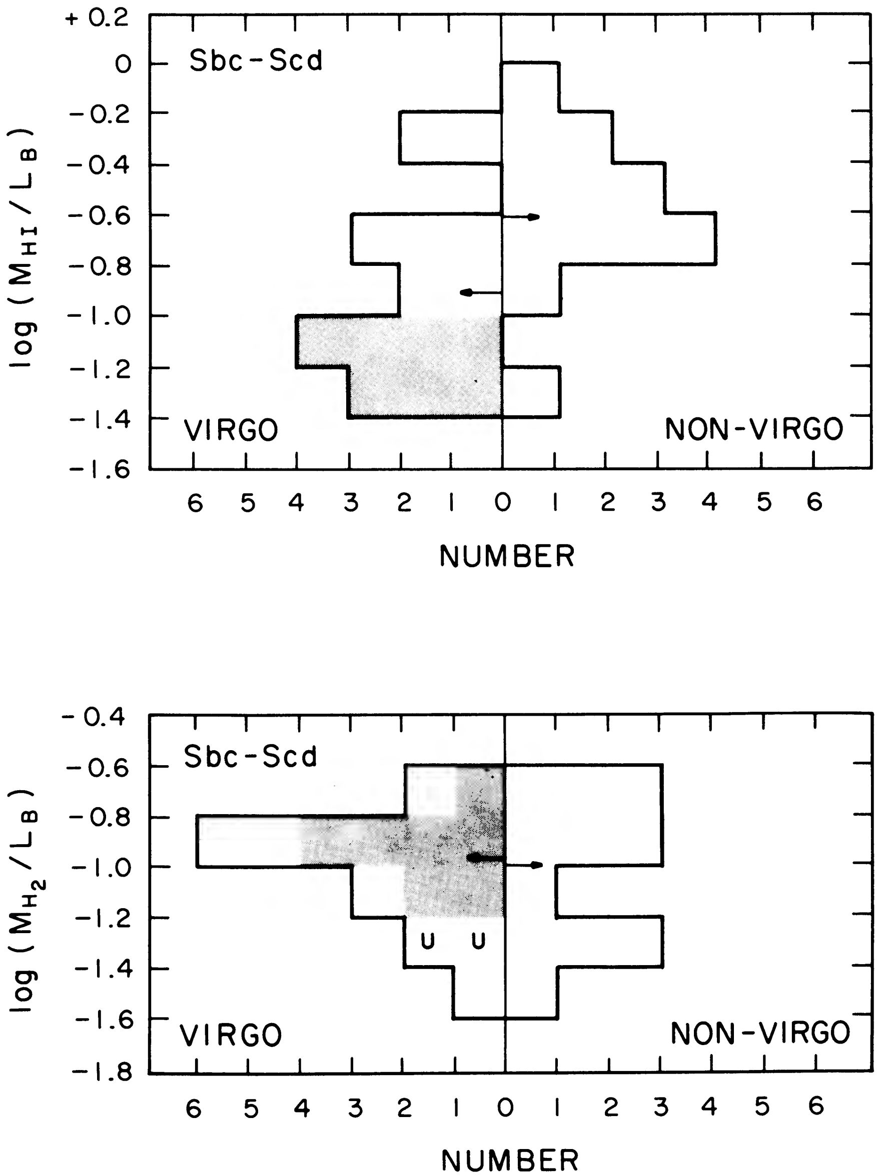


FIG. 2.—Histograms of atomic and molecular gas masses of Virgo and non-Virgo Sbc–Scd galaxies, normalized by their optical luminosities, $L_B$. A rank-sum test confirms that the $M_{\mathrm{H\,I}}/L_B$ distributions are different at the 99% confidence level, but that the $M_{\mathrm{H}_2}/L_b$ distributions are not significantly different. The shaded regions indicate Virgo galaxies which have an H I deficiency value greater than 0.4. $U = 2\ \sigma$ upper limit. The arrows mark the mean of each distribution. The upper limits in the Virgo sample have not been included in the mean. Their inclusion decreases $\log(M_{\mathrm{H}_2}/L_B)$ by 0.04. Galaxies in the comparison sample are the following NGC galaxies: 253, 2276, 2339, 3079, 3628, 3893, 4631, 5194, 6946, 7541, and IC 342. For references, see Kenney and Young (1985) and Young *et al.* (1986).

deficient in molecular gas. However, we note that many early-type galaxies have only upper limits on CO emission (Verter 1985). Until a sensitive search for CO emission in many galaxies of this type is made, it is not possible to decide whether the molecular gas content of these two Virgo systems is normal or deficient.

the radial extent of CO emission. If the molecular gas is removed anywhere, it would be most easily removed far out in the disk, where the gravitational potential is weaker. To test this, we have computed the diameter at which the CO emission falls to $\int T_R^* \, dv = 1$ K km s$^{-1}$, which roughly corresponds to an $H_2$ surface denstiy of $4 \times 10^{20}$ molecules cm$^{-2}$ (Young and Scoville 1982). These CO diameters, normalized to H I diameters, at a surface density of $\sim 5 \times 10^{19}$ atom cm$^{-2}$ (van Gorkom and Kotanyi 1985), are presented as a function of the distance from M87 in Figure 4. The relative values of $D_{\mathrm{CO}}/D_{\mathrm{H\,I}}$ are not strongly affected by the particular choice of CO or H I isophotal level. Galaxies with large values of $D_{\mathrm{CO}}/D_{\mathrm{H\,I}}$ are those which are H I-deficient. The preponderance of galaxies in the Virgo core with large values of $D_{\mathrm{CO}}/D_{\mathrm{H\,I}}$ suggests that H I-deficient Virgo spirals have roughly normal molecular gas distributions.

The existence of a large population of Virgo spirals with small amounts of atomic gas relative to their molecular gas argues that the atomic gas is deficient with respect to not only the stars, but also with respect to the denser component of the

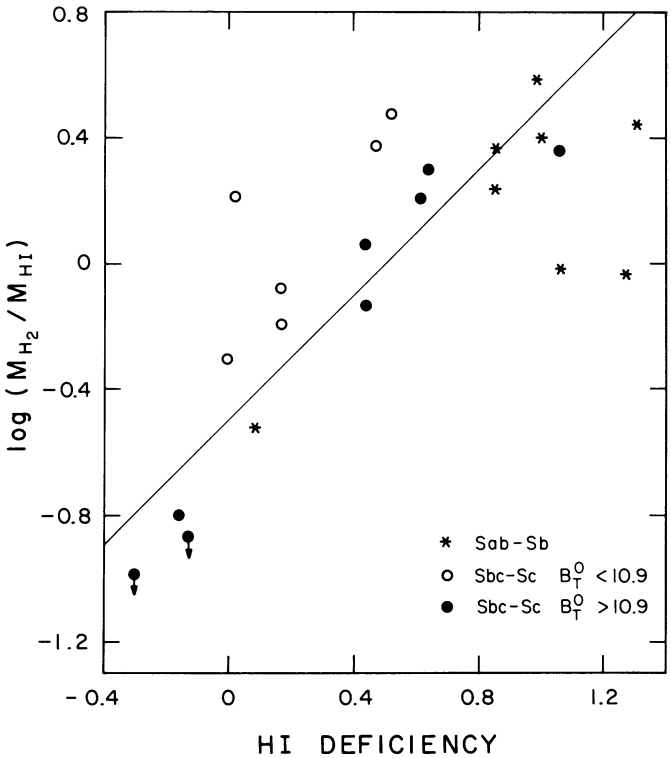


FIG. 3

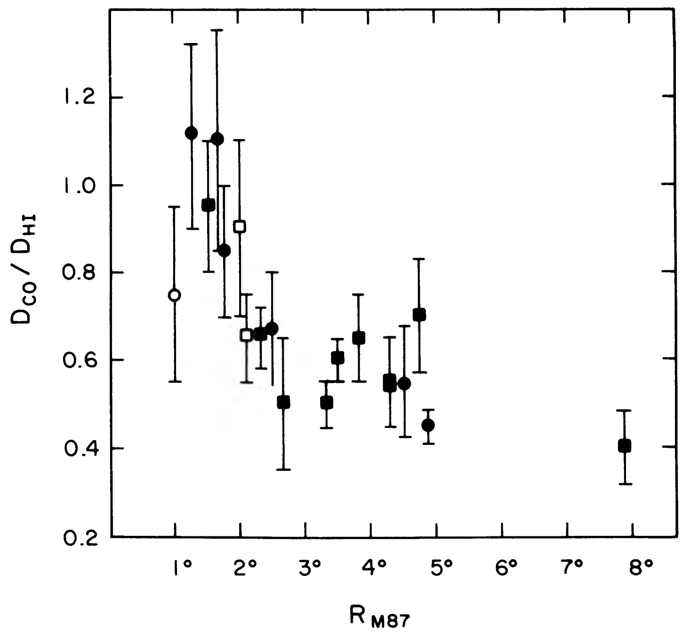


FIG. 4

FIG. 3.—Logarithm of molecular to atomic gas mass ratio vs. H I deficiency parameter for Virgo sample. The line has a slope of 1, which denotes a normal $H_2$ content. It has been placed to roughly fit the less luminous Sbc–Scd galaxies.

FIG. 4.—CO diameters normalized by their H I diameters, vs. distance from M87. Diameters are defined in text and are uncorrected for inclination. Squares denote types Sbc–Sc; circles denote types Sab–Sb; open symbols indicate galaxies whose $D_{CO}/D_{H\,I}$ may be affected by an interaction with a nearby galaxy.

interstellar medium. This is readily explained by an atomic gas removal event, but cannot easily be explained by less atomic gas infall during the last few billion years (Kennicutt 1983; Tully 1985), since molecular clouds form from atomic gas. Furthermore, the normal molecular gas contents in severely H I–deficient galaxies are consistent with a mechanism which removes the low-density atomic gas primarily from the outer parts of the disk but leaves the high density molecular gas unscathed. Asymmetric H I distributions in Virgo (Warmels 1985) and a correlation between H I deficiency and cluster X-ray luminosity in nine clusters (Giovanelli and Haynes 1985) are evidence that the hot intracluster medium has caused the removal of the atomic gas.

Ram pressure stripping (Gunn and Gott 1972), thermal evaporation (Cowie and Songalia 1977), and turbulent viscous stripping (Nulsen 1982) are three processes by which intracluster gas can theoretically remove interstellar gas. Ram pressure stripping is expected to remove atomic gas, but spare molecular clouds. In order for a gas cloud to be stripped by ram pressure, it is easily shown that $N \leq n_{ICM} v_\perp^2/[2\pi G \sigma_{TOT}(r)]$, where $N$ is the column density of disk gas, $n_{ICM}$ is the particle density of the intracluster medium, $v_\perp$ is the component of the galaxy's velocity through the ICM which is perpendicular to the disk, and $\sigma_{TOT}(r)$ is the total surface mass density of the disk at a galactocentric distance $r$. Most of the mass of molecular gas in our own Galaxy is contained in several thousand giant molecular clouds (GMCs) with $D \geq 20$ pc, $M \geq 10^5\ M_\odot$, and $N \geq 3 \times 10^{22}$ nuclei cm$^{-2}$ (Sanders, Scoville, and Solomon 1985). Molecular clouds like these at $r = 10$ kpc, where $\sigma_{TOT} \approx 0.03$ g cm$^{-2}$ (Bahcall, Schmidt, and Soneira 1983), would survive a passage as close as 1° from M87, where $n_{ICM} \approx 10^{-3}$ cm$^{-3}$ (Gorenstein *et al.* 1977; Forman *et al.* 1979) even if our galaxy were moving face-on through the cluster at a velocity equal to twice the spiral velocity dispersion of 800 km s$^{-1}$ (Huchra 1985).

The effects of thermal evaporation and turbulent viscous stripping on a multiphase interstellar medium are beyond the scope of this *Letter*, but several properties of the molecular cloud population make them less susceptible than atomic gas clouds to removal. Molecular clouds are colder, denser, and have a smaller scale height than H I. Having atomic gas surround molecular clouds means that the atomic gas can act as a buffer layer between molecular clouds and the ICM, partially shielding the molecular clouds from thermal evaporation and turbulent instabilities. Finally, the centrally peaked molecular gas distributions mean that more $H_2$ exists in the inner regions of the galaxy where the gravitational force binding it to the disk is greater. Since none of these mechanisms are effective in removing molecular clouds, it is not surprising that they have resisted removal.

It is perhaps more surprising that the molecular gas has not yet responded to the atomic gas removal. Even though the spiral fraction of the Virgo Cluster is dynamically young (e.g., Tully and Shaya 1984; Huchra 1985), the existence of a large number of H I–deficient galaxies indicates that the gas removal events have taken place over at least a cluster crossing time, which is $\sim 10^9$ yr in Virgo. Normal CO in these H I–deficient galaxies indicates that the molecular gas content has not responded to the atomic gas removal in $\sim 10^9$ yr. This has two possible interpretations. One is that the atomic gas is not significantly depleted over the region where CO is detected, and radial flows of gas are insignificant. The second possibility is that the lifetime of the molecular phase is $\geq 10^9$ yr. While it is undoubtedly true that an individual GMC does not remain unaltered for $10^9$ yr due to the disruptive events associated with star formation, it may be that the bulk of molecular material is not destroyed. Previous estimates of molecular phase lifetimes range from $10^7$ yr (Blitz and Shu 1980) to $10^9$ yr (Scoville and Hersh 1979). High-resolution H I maps are needed in order to properly distinguish between these possibilities.

We thank Drs. Martha Haynes, Rob Kennicutt, John Kwan, John Stauffer, and Steve Strom for helpful discussions. The Five College Radio Astronomy Observatory is operated with support from the NSF under grant AST-82-12252 and with the permission of the Metropolitan District Commission, Commonwealth of Massachusetts.

## REFERENCES

Allen, C. W. 1973, *Astrophysical Quantities* (London: Athlone).
Bahcall, J. N., Schmidt, M., and Soneira, R. N. 1983, *Ap. J.*, **265**, 730.
Blitz, L., and Shu, F. H. 1980, *Ap. J.*, **238**, 148.
Cowie, L. L., and Songalia, A. 1977, *Nature*, **266**, 501.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press) (RC2).
de Vaucouleurs, G., and Pence, W. D. 1979, *Ap. J. Suppl.*, **40**, 425.
Dickman, R. L., Snell, R. L., and Schloerb, F. P. 1986, *Ap. J.*, submitted.
Forman, W., Schwarz, J., Jones, C., Liller, W., and Fabian, A. C. 1979, *Ap. J. (Letters)*, **234**, L27.
Giovanelli, R., and Haynes, M. P. 1983, *A.J.*, **88**, 881.
______. 1985, *Ap. J.*, **292**, 404.
Gorenstein, P., Fabricant, D., Topka, K., Tucker, W., and Harnden, F. R., Jr. 1977, *Ap. J. (Letters)*, **216**, L95.
Gunn, J. E., and Gott, J. R. 1972, *Ap. J.*, **176**, 1.
Haynes, M. P., Giovanelli, R., and Chincarini, G. L. 1984, *Ann. Rev. Astr. Ap.*, **22**, 445.
Helou, G., Giovanardi, C., Salpeter, E. E., and Krumm, N. 1981, *Ap. J. Suppl.*, **46**, 267.
Helou, G., Hoffman, G. L., and Salpeter, E. E. 1984, *Ap. J. Suppl.*, **55**, 433.
Huchra, J. P. 1985, in *ESO Workshop on the Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 181.
Kenney, J. D., and Young J. S. 1985, in *ESO Workshop on the Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 165.
Kennicutt, R. C. 1983, *A.J.*, **88**, 483.
Nulsen, P. E. J. 1982, *M.N.R.A.S.*, **198**, 1007.
Sandage, A., and Tammann, G. A. 1981, *Revised Shapley-Ames Catalog of Bright Galaxies* (Washington: Carnegie Institution) (RSA).
Sandage, A., Binggeli, B. and Tammann, G. A. 1985, *A.J.*, **90**, 395.
Sanders, D. B., Scoville, N. Z., and Solomon, P. M. 1985, *Ap. J.*, **289**, 373.
Scoville, N. Z., and Hersh, K. 1979, *Ap. J.*, **265**, 148.
Tully, R. B. 1985, in *ESO Workshop on the Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 385.
Tully, R. B., and Shaya, E. 1984, *Ap. J.*, **281**, 31.
van Gorkom, J., and Kotanyi, C. 1985, in *ESO Workshop on the Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 61.
Verter, F. 1985, *Ap. J. Suppl.*, **57**, 261.
Warmels, R. H. 1985, in *ESO Workshop on the Virgo Cluster of Galaxies*, ed. O.-G. Richter and B. Binggeli (Garching: ESO), p. 51.
Young, J. S., Schloerb, F. P., Kenney, J. D., and Lord, S. D. 1986, *Ap. J.*, in press.
Young, J. S., and Scoville, N. Z. 1982, *Ap. J.*, **258**, 467.

JEFFREY D. KENNEY and JUDITH S. YOUNG: Department of Physics and Astronomy, Lederle Graduate Research Center Tower B, University of Massachusetts at Amherst, Amherst, MA 01003