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Molecular Gas and Star Formation in HI-Deficient Virgo Cluster Galaxies

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ABSTRACT Mapping of the CO emission line in 42 Virgo cluster galaxies reveals that the molecular gas contents and distributions are roughly normal in severely HI-deficient Virgo spirals. The survival of the molecular component mitigates the impact of the HI-stripping on star formation and subsequent galactic evolution. For spirals which are deficient in HI by a factor of 10, far-infrared, Hα line, and non-thermal radio continuum luminosities are lower by no more than a factor of 2. The fact that the inner galactic disks are stripped of HI, while CO is normal, suggests that the lifetime of the molecular phase is $\sim 10^9$ years in the inner regions of luminous spirals.

1. INTRODUCTION & OBSERVATIONS

Many spiral galaxies in the Virgo cluster have far less atomic gas (HI) than typical isolated spirals, probably because the galactic atomic gas is stripped away as the galaxies rush through the intracluster gas surrounding M87 (for a review, see Haynes, Giovanelli, and Chincarini 1984). Since many of these galaxies appear to have lost over 90% of their original HI supply, the evolution of Virgo galaxies has unquestionably been altered to some degree by the harsh cluster environment (e.g. Kennicutt 1983). However, the fate of star formation in HI-deficient galaxies depends critically on the response of the molecular gas to the HI-stripping event: in luminous spirals, molecular gas is a significant fraction of the total interstellar gas mass, and is the component of the interstellar medium out of which stars form.

To determine the fate of molecular gas in HI-deficient galaxies, we have mapped CO(J=1→0) emission in 42 Virgo spirals with the 14-meter telescope of the Five College Radio Astronomy Observatory (HPBW=45"). All Sa-Sm galaxies brighter than B_T^o=12.0 in a 16°x16° field centered on M87 were surveyed in 3-9 positions along the major axis. Of the 42 galaxies surveyed, 33 were detected in at least one position. Both the radial distribution of CO emission and the total CO flux have been determined from the observations by modeling the sources to correct for inclination and source-beam coupling. Results for a subset of the present sample, focussing on the normal CO emission in the HI-deficient galaxies, have been published elsewhere (Kenney and Young 1985, 1986). In this paper, we concentrate on the relationship of the gas content to the present star formation in the HI-deficient Virgo spirals.

2. RESULTS

2.1. CO and Tracers of Star Formation vs. HI Deficiency

As a measure of the HI content of Virgo galaxies, we employ the HI deficiency

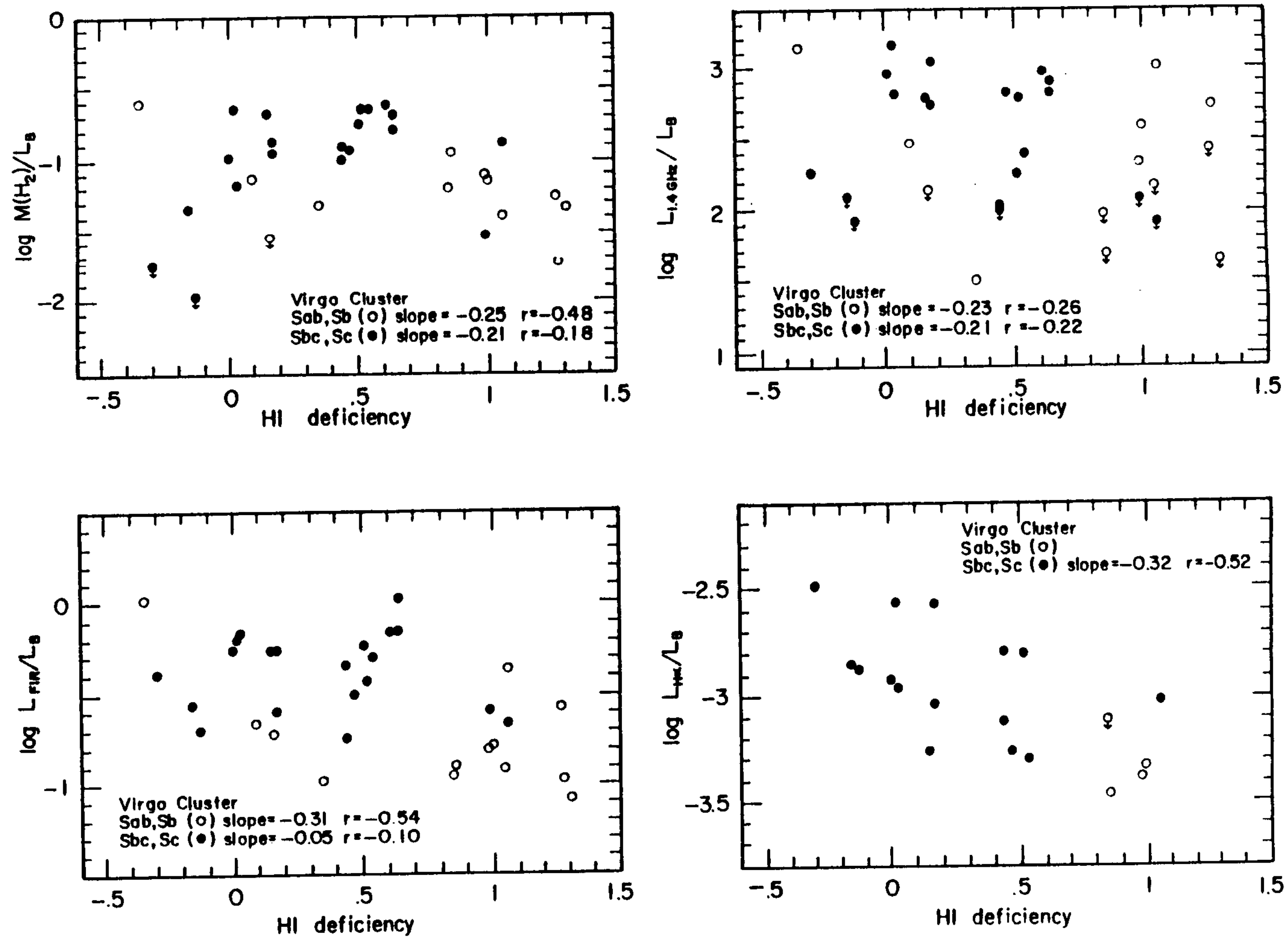

Figure 1. HI deficiency vs. H_2 masses; FIR, radio continuum, and Hα luminosities, all normalized to blue luminosities. The least squares slopes and correlation coefficients (r) have been computed using the 2σ upper limit values for non-detections. Omitting the upper limits does not significantly change the slope or correlation coefficient of any of the fits. (a) H_2 mass is assumed to be proportional to the CO luminosity. Units are $M_\odot/L_\odot$. (b) FIR luminosity derived from single thermal component fit to coadded 60μm and 100μm IRAS fluxes. (c) 1.4 GHz radio continuum. (d) Hα+[NII] luminosities. References--HI: Helou et al. (1981, 1984); Giovanelli and Haynes (1983, 1985). Blue light: RC2 (1976). Far-infrared: IRAS coadds (1986). 1.4 GHz radio continuum: Kotanyi (1980). Hα+[NII]: Kennicutt and Kent (1983).

parameter, as formulated by Giovanelli and Haynes (1983). Its definition is: HI def = log[M(HI expected)/M(HI actual)], where M(HI expected) is the HI mass of a typical isolated galaxy of the same morphological type and optical diameter. The HI deficiency is a logarithmic ratio, so that HI def = 0 (±0.3) denotes a normal HI content, and HI def = 1.0 denotes a galaxy with 10 times less HI than normal. In Figure 1, the HI deficiency is compared with global measures of CO emission and three tracers of current star formation. In order to compensate for the range in galaxy masses, we normalize these quantities by the blue optical luminosity.

Figure 1a shows that the CO luminosities of the HI-deficient galaxies are roughly normal, since the L_{CO}/L_B ratios are similar for the HI-normal and severely HI-deficient galaxies. Further discussions of the CO luminosities and distributions in Virgo spirals, including comparisons with non-Virgo spirals, are presented in Kenney and Young (1985, 1986). Stark et al. (1986) also find normal CO emission in Virgo spirals. Throughout this paper, the H_2 mass is assumed to be proportional to the CO luminosity ($\sigma(H_2) \sim 3.9 \int T_R(CO)dv\ M_\odot pc^{-2}$; Dickman, Snell, and Schloerb 1986). Although the $^{12}CO(J=1\rightarrow0)$ line is generally optically thick, the fact that more massive molecular clouds have larger linewidths (at least in our galaxy, e.g. Sanders, Scoville, and Solomon 1985) allows the use of CO emission as a valid tracer of molecular mass. The $CO\rightarrow H_2$ conversion does depend linearly on the mean gas temperature (and weakly on the mean gas density and the cloud mass spectrum). However, we find that the $S_{60\mu m}/S_{100\mu m}$ ratios (a measure of dust temperature) are uncorrelated with HI deficiency. Thus, it is unlikely that the $CO\rightarrow H_2$ conversion is significantly different in the HI-deficient galaxies.

Figures 1b and 1c show that the far-infrared and 1.4 GHz radio continuum luminosities are not strongly correlated with HI deficiency. Figure 1d indicates some degree of correlation between HI deficiency and Hα luminosity for Virgo Sc's, as discovered previously by Kennicutt (1983). However, the maximum slope in any of these relations, of -0.32 in the log, means that galaxies which are HI-deficient by a factor of 10 are deficient in current star formation by a maximum of a factor of 2. We argue below that this is due to the survival of the molecular component.

2.2 Radial Distributions of Gas, New Stars and Old Stars

That the survival of H_2 is responsible for maintaining high global rates of star formation despite the severe HI deficiencies is elucidated by the radial distributions in Figure 2. There are 2 features of the radial distributions which are worth emphasizing: 1) In all galaxies, the distributions of CO, HII regions, and radio continuum emission are similar. This demonstrates that star formation occurs where the molecular gas exists. 2) In galaxies with normal amounts of HI, the surface densities of HI and H_2 are typically equal at some radius. In the severely HI-deficient spirals, the surface density of HI is significantly below that of H_2 over the entire region where CO is detected.

One reason that the molecular gas has resisted removal, while the atomic gas has not, is that the HI and H_2 generally have such different distributions. The gravitational force per unit area binding a gas cloud to a galactic disk is approximately $2\pi G\sigma_{TOT}(R)\sigma_{gas}$, where σ_{gas} is the gas mass surface density, and $\sigma_{TOT}(R)$ is the total mass surface density, which is a function of galactocentric radius R. Typically, a large fraction of a galaxy's molecular gas resides in the inner galaxy, where $\sigma_{TOT}(R)$ is large. Most of the HI exists in the outer galaxy, and thus is more easily removed, since $\sigma_{TOT}(R)$ is smaller.

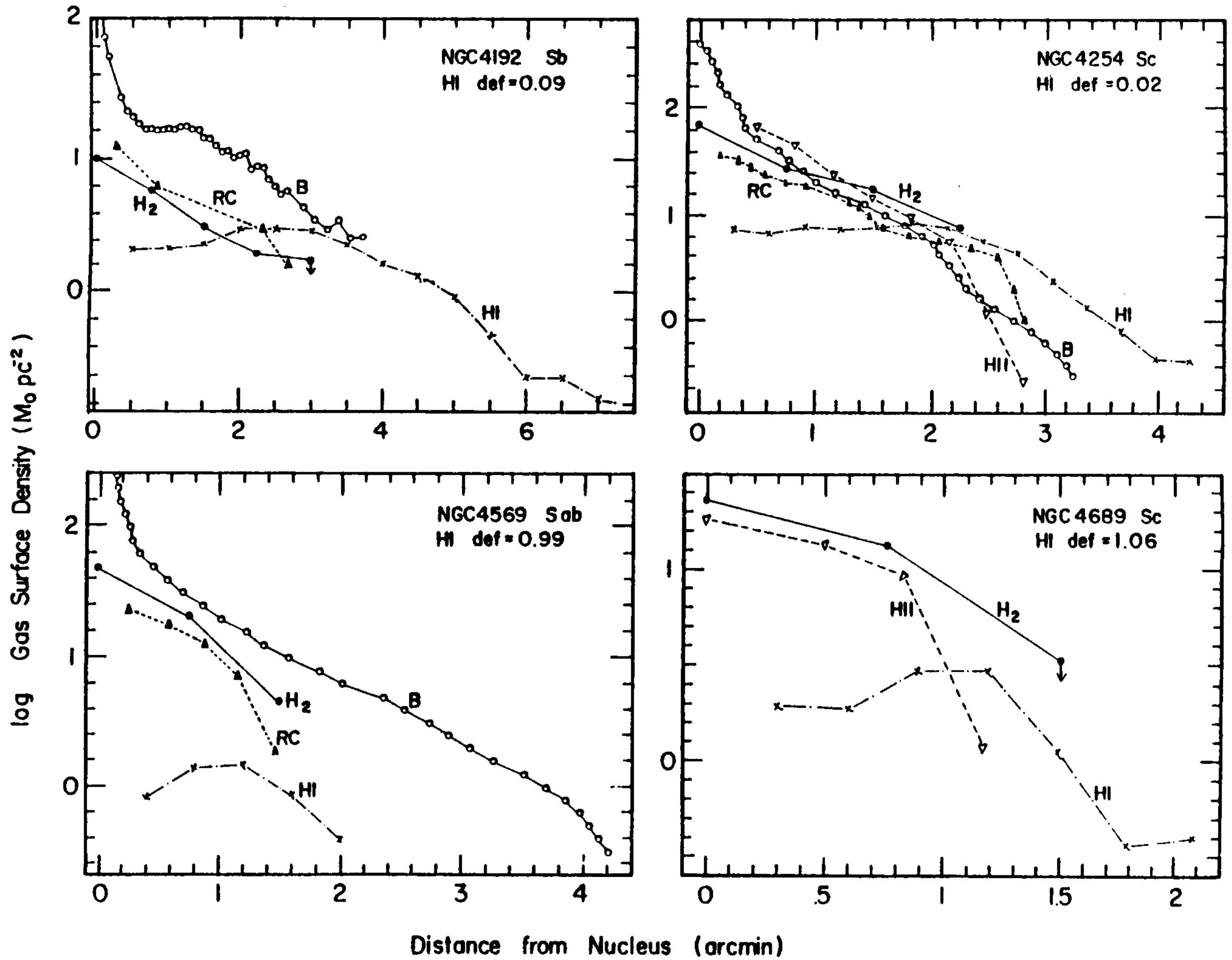

Figure 2. Radial distributions of CO (H_2), HI, 1.4 GHz radio continuum (RC), HII regions (HII), and blue light (B) in 4 Virgo spirals, selected to show a range in HI deficiency and morphological type. The vertical scaling for HI and H_2 is $M_\odot$ pc^{-2}. All other quantites have been scaled by an arbitrary factor which gives a good fit to the H_2 distribution in 3 luminous Sc galaxies. Although the scaling factor for B, RC, and HII is arbitrary, it is the same for every galaxy. References--HI: Warmels (1986). Blue light: Whitmore and Kirshner (1982); Fraser (1977). 1.4 GHz continuum: Condon (1983); Warmels (1986). HII region counts from Hodge and Kennicutt (1983), normalized by global Hα+[NII] fluxes (Kennicutt and Kent 1983). The HII region counts may be underestimated in the galaxy centers due to plate burnout.

The greater column density of molecular clouds (and corresponding greater σ_{gas}) is the second property of molecular gas which makes it more difficult to strip than atomic gas. This property is relevant, since even the inner regions of the Virgo galaxies have less HI, as shown in Figure 3a. This figure displays the (global) HI deficiency vs. the mean HI surface density over the inner half of the optical disk, normalized to the typical value for a more isolated galaxy of the same type (Warmels 1986). The slope of this relation, -0.38 in the log, means that galaxies which are globally HI-deficient by a factor of 10, are HI-deficient in the inner galaxy by a factor of ~2-3. Thus even the inner galaxy, where the bulk of the molecular gas exists, has been stripped of atomic gas. Figure 3b shows explicitly that the $M(HI)/M(H_2)$ ratio is significantly lower over the region where CO is detected (which is typically $D_0/4$) in the HI-deficient spirals. The slope of this relation, -0.50 in the log, indicates that the inner galaxy HI deficiency is the same (within the uncertainties) whether measured with respect to the HI in isolated galaxies, or with respect to the molecular gas.

2.3 The Long Lifetime of the Molecular Gas Phase

While perhaps unsurprising that the dense H_2 has survived the stripping, it is significant that the molecular gas has not yet responded to the atomic gas removal. The large number of Virgo galaxies with small HI/H_2 ratios suggests that the molecular gas has not responded during a cluster crossing time (~10^9 years), which is approximately how long the stripping events have been going on.

Inasmuch as the HI-deficient Virgo galaxies can be considered once-normal spirals subjected to modification in a cluster 'laboratory', we may conclude that the molecular phase is long-lived in the inner disks of all luminous (non-starburst) spiral galaxies. Energetic events associated with star formation

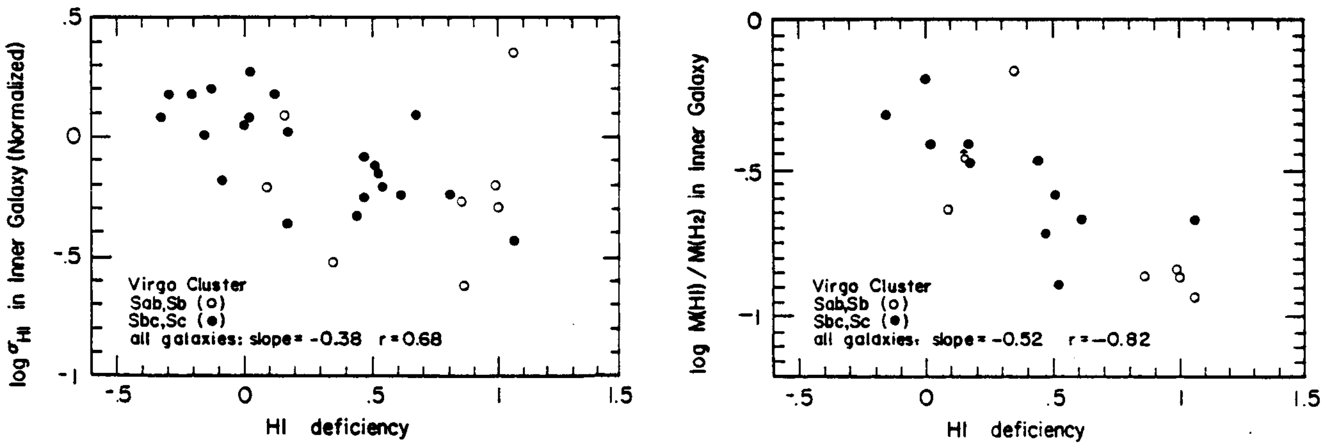

Figure 3. (a) Mean HI surface density for Virgo spirals over the inner half of the optical disk (out to a radius of $D_0/4$, where D_0 is the optical diameter from the RC2), normalized to the typical value for a more isolated galaxy of the same type (Warmels 1986), vs. HI deficiency. (b) HI/H_2 mass ratio, over the region where CO is detected, vs. HI deficiency.

undoubtedly act to partly ionize and disrupt molecular clouds, but the conversion of H_2 back into HI appears to be an inefficient process in these galaxies. Apparently, once gas enters the molecular phase in the inner regions of luminous spiral galaxies, it tends to remain molecular for $\sim 10^9$ years. The predominant disruptive influence of star formation on molecular clouds may be to break apart the cloud into smaller fragments.

3. CONCLUSIONS

1) CO fluxes and distributions are roughly normal in HI-deficient Virgo cluster spirals. This is easily understood, since molecular clouds are difficult to strip. Two charactersistics of molecular gas are responsible for its survival: its high surface density (with respect to most of the HI), and its location deep in the gravitational well of the galaxy.

2) The survival of the molecular component mitigates the impact of HI removal on star formation and subsequent galactic evolution. In galaxies which are globally HI-deficient by a factor of 10, global tracers of star formation (FIR, radio continuum, $H\alpha$) are lower by no more than a factor of 2.

3) Atomic gas has been stripped even in the inner galaxy, where the molecular gas resides. Molecular gas has not significantly responded to the HI removal in over a cluster crossing time, or $\sim 10^9$ years. This implies that gas in the inner regions of luminous spirals does not cycle rapidly between the atomic and molecular phases. Instead, once a typical nucleon enters the molecular phase, it remains molecular for $\sim 10^9$ years.

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