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HIGH CHEMICAL ABUNDANCES IN H I DEFICIENT SPIRALS OF THE VIRGO CLUSTER [1]

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RESUMEN

Nuevas observaciones de regiones H II, junto con datos ya publicados, permiten obtener la abundancia de O en 9 galaxias espirales tardías del cúmulo de Virgo. Las galaxias se dividen en 3 grupos de acuerdo con su deficiencia de H I relativa a espirales de campo normales. Generalmente, las galaxias más deficientes en H I son las más cercanas al centro del cúmulo. Las espirales más externas, con contenido normal de H I, muestran abundancias y gradientes radiales de abundancias similares a los de las galaxias de campo. Las galaxias deficientes en H I muestran abundancias de O mayores por ≈ 0.3 dex y gradientes relativamente planos. Las galaxias con deficiencia intermedia tienen abundancias de O intermedia. Estos resultados confirman y aclaran indicaciones previas de que las galaxias espirales, pertenecientes a un cúmulo, evolucionan hacia mayores abundancias químicas. Modelos sencillos de evolución química muestran que, recortar la caída de material en las espirales del cúmulo, puede explicar en parte las diferencias de abundancias pero parece haber necesidad de algunos otros mecanismos.

ABSTRACT

New spectroscopic observations of H II regions, together with published data, are used to derive interstellar O abundances in 9 late-type spiral galaxies in the Virgo cluster. The galaxies are divided into 3 groups according to their deficiency of H I relative to normal field spirals. Generally, the most H I deficient galaxies are closest to the cluster core. The outlying spirals with normal H I content show abundances and radial abundance gradients similar to those in field spirals. The H I deficient galaxies show abundances larger by about 0.3 dex and relatively flat radial gradients. The galaxies with an intermediate degree of H I deficiency are intermediate in O abundance. These results confirm and clarify earlier indications that spirals evolve to higher chemical abundances in the cluster environment. Simple chemical evolution models indicate that curtailment of infall into spirals in the cluster core may explain part of the abundance differential, but there appears to be a need for other mechanisms.

Key words: **GALAXIES: ABUNDANCES — GALAXIES: CLUSTERING — GALAXIES: EVOLUTION — H II REGIONS**

[1] Based on observations obtained at the Multiple Mirror Telescope, a joint facility of the University of Arizona and the Smithsonian Institution.

1. INTRODUCTION

The details of the chemical evolution of the disks of spiral galaxies remain uncertain. The importance of continuing infall, radial flows, escape of supernova debris, and mergers are among the issues under discussion. Observational constraints on models of galactic evolution include colors, Hα luminosities, and chemical abundances. Spectrophotometry of giant H II regions in spiral galaxies has revealed that heavy element abundances, such as the O/H ratio, generally decrease outwards across the galactic disk. The overall abundance level increases with increasing galactic luminosity, increasing circular velocity, and earlier Hubble type (see Zaritsky, Kennicutt, & Huchra 1994, ZKH; and references therein). Spiral galaxies are affected in various ways by the environment of a rich cluster of galaxies (see reviews by Haynes 1990 and Whitmore 1990). Effects include a reduction in the H I content, particularly at larger galactocentric radii, redder colors, and weaker Hα emission for a given morphological type (Kennicutt 1983). These effects, in turn, raise the question of whether the chemical abundances are affected by the cluster environment.

Shields, Skillman, & Kennicutt (1991, SSK) observed H II regions in several Sc galaxies in the Virgo cluster to look for systematic differences between their abundances and those of field spirals. Because the H II regions are too faint to allow measurement of electron temperatures, they derived oxygen abundances from the sum of the intensities of the [O II] and [O III] nebular lines, $R_{23} \equiv$ ([O II]+[O III])/Hβ. The results indicated abundances higher by about a factor of two over comparable field spirals. SSK suggested that O/H in the field galaxies might be held down by metal-poor gas falling into the galaxy, or flowing radially inward from the outer reaches of the gaseous disk. Neither process is likely to be happening in the cluster environment. The intracluster gas is hot, metal-enriched gas that should be difficult for cluster galaxies to accrete, especially in view of their high velocities. The outer H I disks have, by definition, been removed, perhaps by ram pressure (Warmels 1986, and references therein.) Henry et al. (1992, HPLC) studied the Virgo spiral NGC 4303 and found abundances comparable with those of field spirals. Henry, Pagel, & Chincarini (1994, HPC) studied another Virgo Sc galaxy, NGC 4254, and found evidence for some elevation of O/H, relative to field spirals. Taking NGC 4254, NGC 4303, and NGC 4321 together, they found that the value of O/H extrapolated to the center of the galaxy was roughly $0.15 - 0.20$ dex larger for the Virgo galaxies than for a small sample of field galaxies.

To clarify the situation regarding abundances in Virgo cluster spirals, we have conducted further observations. Details of this work will be presented elsewhere (Skillman et al. 1995, SKSZ). These observations were designed to address the question of whether the Virgo abundance differential is real, and whether it is found in all galaxies in the cluster, or only those that show other evidence for modification by the cluster environment. We give here a brief summary of the observational results and some simple theoretical considerations.

2. OBSERVATIONS

We assembled a list of 9 Virgo spirals characterized by a range in distance from the cluster center (M87) and H I deficiency. These we subdivided into three groups: (1) galaxies clearly deficient in H I (NGC 4501, 4571, and 4689); (2) intermediate cases (NGC 4254, 4321, and 4654); and (3) galaxies in the outskirts of the cluster with normal H I distributions (NGC 4303, 4651, and 4713). Table 1 shows the distance from M87 and D_H/D_O averaged for each of the three groups. Here, D_H/D_O is the ratio of the diameter of the H I disk at Σ_{HI} = 1 $M_\odot$ pc^{-2} (Warmels 1986) to the optical diameter (de Vaucouleurs et al. 1991, RC3). The Σ_{HI} distributions were examined as a function of radius, normalized to the photometric radius, R_O (RC3). In NGC 4689 and 4571, the surface density is lower at all radii than in typical field spirals of comparable type; in NGC 4501, the surface density is depressed outside $\sim 0.5 R_O$. The three intermediate galaxies show depressed Σ_{HI} outside R_O, and the three "normal" Virgo spirals show Σ_{HI} comparable with field spirals at all radii.

Spectrophotometry for 30 additional H II regions in the Virgo spirals was obtained in April 1991 and May 1992, using the Blue Channel Spectrograph on the Multiple Mirror Telescope (MMT). The H II regions were identified from Hα CCD images obtained by Kennicutt using a focal reducer on the Steward Observatory 2.3-m telescope. Preference in selection was given to bright H II regions which covered the maximum radial extent within each galaxy. The observing setup at the MMT was virtually identical to that described in SSK. The Balmer lines were corrected for underlying stellar absorption with an assumed equivalent width of 2 Å (McCall, Rybski, & Shields 1985, MRS), and the reddening was determined from the relative Balmer line strengths.

Combined with published spectra (SSK; MRS; HPLC; HPC), the new observations provide data for 70 H II regions in the nine Virgo galaxies of our sample, with at least four H II regions observed in each galaxy. For the galaxies in common, our line intensities agree well with those of Henry et al. and MRS. Abundances were derived from the values of R_{23} for all 70 H II regions with the aid of the same empirical calibration used by

ZKH. This is an average of three calibrations by Edmunds & Pagel (1984), MRS, and Dopita & Evans (1986). Also in the manner of ZKH, these abundances were fit with a linear relation in log O/H versus radius and a characteristic value $(O/H)_o$ at R = 0.4 R_O was derived from the fit for each galaxy. These procedures allow a direct comparison of the Virgo results with those of ZKH for a large sample of field spirals.

3. RESULTS

Table 1 shows the resulting values of $(O/H)_o$ averaged for the three galaxies in each of the three groups of Virgo spirals. Also shown are the values of the spectral parameter log (R_{23}) averaged for the three H II regions closest in radius to 0.4 R_O in each galaxy, and then averaged over the three galaxies in each group. (The errors are the standard error of the mean based on the dispersion in the values for each galaxy in a group of three.) The mean R_{23} progressively decreases, and $(O/H)_o$ increases, from the normal to the intermediate to the H I deficient groups. The H I deficient group differs from the normal group by 0.64±0.16 (1σ) in log R_{23} and by 0.32±0.06 (1σ) in log $(O/H)_o$. There is also a progression in the abundance gradient (dex per R_O) from the normal to the deficient groups. However, any discussion of gradients is complicated by the fact that H II regions are observed out to larger radii in the intermediate and normal galaxies than in H I the deficient galaxies.

TABLE 1

ABUNDANCES AND GRADIENTS IN VIRGO SPIRAL GALAXIES

Group	R_{M87}	D_H/D_O	log R_{23}	log $(O/H)_o$	Gradient
H I Deficient	3.0	0.93	-0.09 ± 0.09	9.28 ± 0.02	-0.34 ± 0.12
Intermediate	3.7	1.32	0.26 ± 0.12	9.14 ± 0.07	-0.62 ± 0.13
Normal	7.3	1.82	0.54 ± 0.13	8.91 ± 0.07	-0.88 ± 0.24

SKSZ also compared the Virgo spirals to the field spirals studied by ZKH. The normal Virgo group shows abundances and gradients comparable with the field sample when these quantities are plotted as functions of galactic absolute magnitude, circular velocity, or Hubble type. The Virgo H I deficient group average abundance is systematically higher than the field sample. Out of the entire sample of 29 field spirals used by SKSZ, together with the present nine Virgo spirals, three of the five most oxygen-rich galaxies are H I deficient Virgo spirals. Compared with the average field galaxy of their respective morphological T-types (RC3), the three H I deficient Virgo spirals have log O/H higher by 0.33. In particular, NGC 4571 exceeds by 0.67 the mean log $(O/H)_o$ for the T=6 galaxies of ZKH.

4. DISCUSSION

These results support and clarify the proposition of SSK that late type Virgo cluster spirals tend to have interstellar abundances ~ 0.3 dex larger than comparable field galaxies. The elevated abundances occur in galaxies near the cluster core with substantial H I deficiencies, i.e., those with independent evidence for environmental modification. This clarification reconciles our work with that of Henry et al. and SSK. HPLC found no evidence for elevated abundances in NGC 4303, in agreement with our observations and the status of this galaxy as an outlying cluster member with normal H I content. HPC found evidence of a mild overabundance in NGC 4254, again consistent with our observations and with this galaxy's intermediate H I content.

SSK suggested two possible causes of the Virgo abundance differential. (1) Persistent infall (e.g., Larson 1972; Gunn 1983) might be holding down the interstellar abundances of field galaxies. When the H I deficient Virgo galaxies enter the hot IGM, such infall ceases, possibly allowing the abundances to rise more rapidly than in the field spirals. (2) Radial flows have also been considered as an important aspect of chemical evolution (e.g., Clarke 1989; Götz & Köppen 1992, and references therein). Gas migrating from the outer, metal-poor H I disk to smaller radii, crosses the presumed star formation boundary radius and undergoes progressive enrichment as it moves inwards. This process would be inhibited when the outer H I disk is removed in the cluster environment, presumably leading to weaker radial gradients and higher overall abundances.

SKSZ considered some simple models aimed at estimating the change in O/H that might result from the cessation of infall in cluster galaxies. These models assumed that a primary element was produced instantaneously with an arbitrary yield per unit mass of star formation. Infall was assumed with a constant or exponentially decreasing rate, and return of gas (with appropriate metallicity) from dying stars was calculated on the basis of the return fractions of Kennicutt, Tamblyn, & Congdon (1994, KTC). Two prescriptions for the star formation rate (SFR) were considered: (1) a linear Schmidt (1963) law, with the SFR given by the gas mass divided by a time constant of 2.5 Gyr; and (2), a requirement of constant gas mass, so that the SFR equals the sum of the infall and return rates. For all models, a present age of 10 Gyr was assumed. For each case, a baseline model for a field Sc galaxy was constructed by requiring that the current values of the star formation parameter, b, and the "Roberts" time, τ_R, agree with typical values. Here, b is the ratio of the present to past average SFR (Scalo 1986); and τ_R is the gas mass divided by the present SFR. Based on observed $B-V$ colors and Hα equivalents widths (Kennicutt 1983), SKSZ used alternative values $b = 0.6$ or 1.0; and they adopted $\tau_R = 2.5$ Gyr (Kennicutt et al. 1994). Corresponding to each field galaxy model with continuing infall, SKSZ computed a case in which infall was abruptly cut off 3 Gyr ago. For models with a linear Schmidt law, the abundances at 10 Gyr are elevated by about 0.15 dex relative to the corresponding model with continued infall. In models with a constant gas mass, the SFR drops severely after infall is cut off, and the abundance shows little further increase. Therefore, at 10 Gyr, O/H is negligibly different from the model with continued infall. Also, $B-V$ is too red, EW(Hα) too small, and τ_R too long in the models with constant M_g and a cutoff of infall.

This study indicates that the abundance differential for Virgo spirals with low H I content is real. As much as half of it may be explained by a cutoff of infall in the Virgo cluster environment, if the SFR rate is governed by a law resembling the linear Schmidt law. However, one or more additional processes apparently must contribute. Radial gas flows are one possibility that merits detailed investigation.

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