THE GAS CONTENT IN DISK GALAXIES THROUGH CENTIMETRIC RADIO, INFRARED AND OPTICAL WINDOWS

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I. ABSTRACT

I wish to discuss two basic questions:
1) what do we know from the observations about the relationships between the physical conditions of the Interstellar medium (ISM) in disk galaxies and their past and present star formation rate, heating of dust and acceleration of relativistic cosmic rays ?
2) are the above relations and mechanisms sensitive to the intergalactic environment in rich clusters of galaxies?

I will discuss these questions by reviewing three topics:
a) gas content versus star formation
b) FIR emission versus star formation
c) radio continuum emission versus star formation

and by discussing weather and how these topics are related to the environment.

II. The available data-base

Recent results and data collected from the literature on all Zwicky galaxies (Zwicky et al, 1961-1968) in 9 nearby ($z < 0.03$) clusters of galaxies and in a relatively isolated region in the Coma Supercluster were merged in a data-base (unpublished). The clusters are: A262, A1367, A1656, A2147, A2151, A2197, A2199, the Cancer and Virgo clusters. These candidates were selected, among well studied clusters, for covering a wide range in richness, spiral content, X-ray luminosity and concentration. The data-base includes 1748 galaxies, representing a homogeneous optically selected sample ($m_p < 15.7$, except in Virgo where $m_p \leq 14.5$). For each galaxy in the data-base the following entries are listed (if available):

1) radio continuum data at 1415 and/or 610 MHz (mainly from the VLA and the WSRT)
2) 21 cm line measurements obtained at Arecibo
3) Far IR (12, 25, 60, 100 μ) observations from IRAS
4) Near IR observations in the J, H, K bands
5) photometry in the visible V, B, U (photographic, J, F) bands from multiaperture or CCD data.
6) measurements of the (integrated)H_α equivalent width.
7) accurate coordinates, morphological type, diameters, redshift.
8) detailed references to the above measurements.

Here we report the preliminary results obtained using the subsample of 817 spiral galaxies (from Sa to Irregulars). The radio, FIR and redshift coverage are almost complete, while the near IR and the optical data are strongly incomplete. In particular it is striking the lack of NIR and H_α information in Virgo, in A262 and in A2197+A2199. The Coma supercluster region alone contains

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457 disk galaxies and it is by far the best studied in our data-base. The observations of this region were in the majority obtained by the author and collaborators in the last four years.

III. a) Gas content and Star Formation

Radial profiles of galaxies have been obtained at several frequencies, namely in CO, H_α, Blue light and HI showing that the radial distribution of H_2 and of the past and present star formation are roughly exponential (see Kennicutt, 1989). On the contrary it is well known that the radial distribution of HI is much flatter and it extends well beyond the optical disk. From this evidence it is tempting to conclude that the star formation rate in galaxies is proportional to the available molecular gas surface density (Schmidt law) as it was proposed 30 years ago by Schmidt (1959). However Kennicutt (1989) showed that such a relation does not apply in reality. His Fig. 8 shows that the dependence is close to proportionality only at high surface densities (in the inner galaxy) while the dependence is much steeper at lower surface densities. Furthermore there is a sharp threshold below which star formation is totally prevented. In conclusion the work of Kennicutt showed that the dependence of the star formation rate on the available gas density is strongly non linear. He determined that the presence of a threshold in the star formation corresponds to a critical density for gravitational instability of the gas, which is governed by the dynamical properties of the disk (see also Guideroni, 1987).

Another puzzling result of Kennicutt (1989) is that, looking at integrated properties of galaxies, he finds no correlation between the H_2 content (properly normalized to the total mass) and the star formation rate. On the contrary a correlation exists between the HI content and the star formation rate. Both results are unexpected from the radial profiles of CO, H_α and HI. The lack of a correlation between molecular H and star formation could result from: 1) problems with the CO as quantitative tracer of the molecular mass; 2) strong dissociation could arise near regions of high star formation rate; 3) absorption could affect H_α measurements (cf. Rowan-Robinson, this meeting). However the existence of a correlation between the star formation rate and the total HI column density it is even more surprising since the two distributions are known to be different. This correlation has been confirmed using UV flux measurement to derive SFR in a sample of isolated galaxies as well as in the cluster A1367 by Donas et al, 1990.

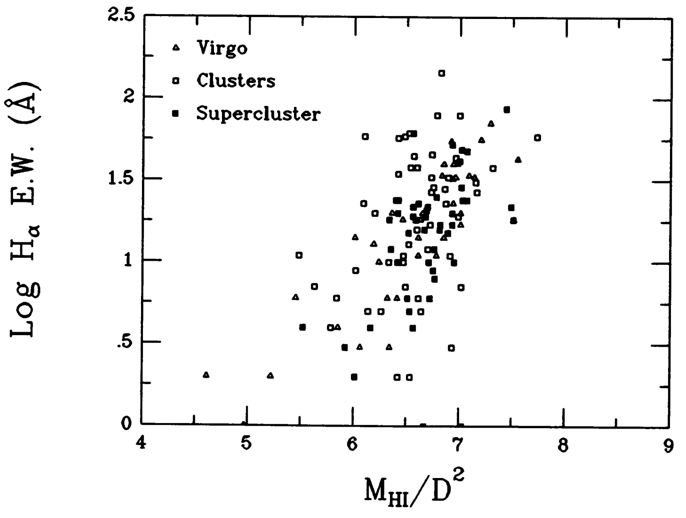

Fig. 1: the correlation between the H_α E.W. and the hybrid HI surface brightness.

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Using a sample of galaxies much larger and independent from the one used by Kennicutt we confirm the existence of the latter linear correlation, as illustrated in Fig. 1. The H_α E.W. (star formation rate) of all galaxies in our data-base is plotted in Fig. 1 versus their hybrid HI surface brightness (the HI mass per unit area determined from the optical diameter). Objects in the deficient clusters are plotted with different symbols to separate them from the isolated ones. The diagram indicates that the star formation rate is roughly proportional to the HI surface density. From this correlation one has to conclude that the primordial gas content (traced by the HI surface density) has still an important role in regulating the SFR in the disk in spite of the difference in the radial distributions of the two quantities.

III. b) gas content and environment

I wish to start this section by mentioning briefly the important results recently obtained in millimeter astronomy in the field of cluster research (see a review in Kenney, 1989, and cf. Young, 1989 for spiral galaxies in general). Unfortunately the only well studied cluster on which most conclusions are based is the Virgo cluster. Stark et al, 1986 observed 47 galaxies in this cluster and found that the CO/HI flux ratio increases toward the cluster center. Kenney and Young (1989), using 40 Virgo galaxies confirmed this result and found that the spatial distribution and the global content of molecular gas is normal in HI deficient spirals. As in isolated galaxies the distribution of H_2 is more concentrated toward the galaxy center than that of HI. The high surface density of molecular gas and its location deep in the gravitational well of the galaxy are responsible for its survival against ram-pressure stripping, even in galaxies travelling at the maximum allowed speed in the dense cluster environment. Casoli et al (this conference) have observed for the first time 18 galaxies in the Coma cluster and found that even in this cluster HI deficient objects have normal H_2 properties.

Strong evidence for environmental induced evolution in galaxies, otherwise so elusive in its observable consequences, comes from HI observations of cluster galaxies. The issue, pioneered by Sullivan et al 1981, was extensively reviewed by Haynes et al, 1984 and perhaps it culminated with the work of Giovanelli and Haynes, 1985. They not only gave definite evidence that global HI deficiency exists in some clusters (5 out of the surveyed 9) but also showed that the HI deficient fraction of galaxies in a cluster correlates with the X-ray luminosity of the cluster diffuse gas. This evidence favors, although it does not prove, the interpretation that HI removal (or ablation) in cluster galaxies is consequent to the dynamical interaction between the fast moving galaxies and the cluster intergalactic medium (IGM), much in the way envisaged in the ram-pressure model proposed by Gunn and Gott (1972) and subsequently adapted by Nulsen (1982) to include turbulence.

Using our data-base (a sample about twice as large than the one used by Giovanelli and Haynes, 1985) we find that their results are fully confirmed. Some degree of HI deficiency (HI def$>$ 0.5) is apparent in all clusters but Cancer and A2151. By far the largest deficiencies are found in the Virgo cluster.

Fig. 2 shows the radial distribution of the HI deficiency in the combined clusters. Only A1367 and Coma have been sampled to large distances from the cluster centers. In all deficient clusters the deficient galaxies concentrate in the inner 1.5-2 Mpc from the center.

I wish to focus the attention once more on Fig. 1 to show that a similar relation between the star formation rate and the HI surface density found for isolated galaxies applies in the HI deficient clusters. This evidence reinforces the conclusion reached in section III a) that the HI surface brightness is an important parameter in regulating the star formation rate in galaxies irrespective of the environmental differences.

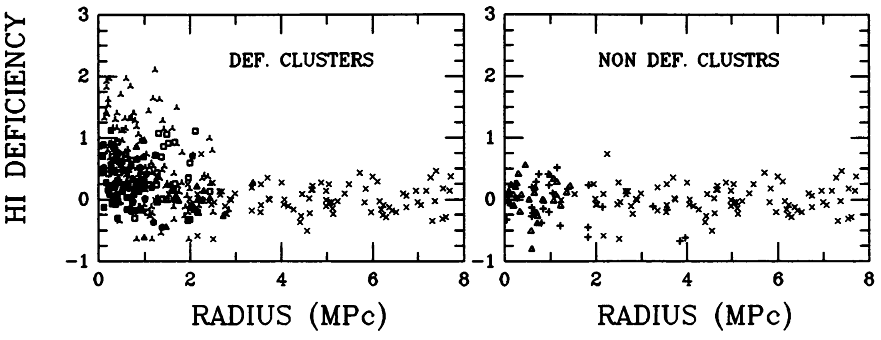

Fig. 2: the radial distribution of the HI deficiency in the deficient clusters (a) and in A2151 and in the Cancer cluster (b). Crosses indicate the bridge between A1367 and the Coma cluster.

III. c) FIR emission and star formation

Far infrared emission from galaxies is generally interpreted as due to radiation by dust heated by the stellar photon field. Several pieces of evidence exist favoring the hypothesis that a major contribution to the dust heating is due to young, massive stars (Gavazzi, Cocito and Vettolani, 1986). Recently Devereux and Young, 1990 concluded that O-B associations are likely to be the responsible for FIR emission.

In this section we study the relationships between the star formation and the emission in the 60 μ Far infrared band found in galaxies belonging to the 9 cluster sample. Using only the relatively small subsample of galaxies detected in the 60 μ band and with available information in the optical we show that the FIR flux (normalized to the flux in the V band in order to avoid a trivial conclusion such as: "bigger galaxies have more of everything") correlates with the H_α equivalent width (Fig. 3) with a slope close to one. Consequently FIR emission can be used as a tracer of the star formation rate (cf. Lonsdale and Helou, 1987).

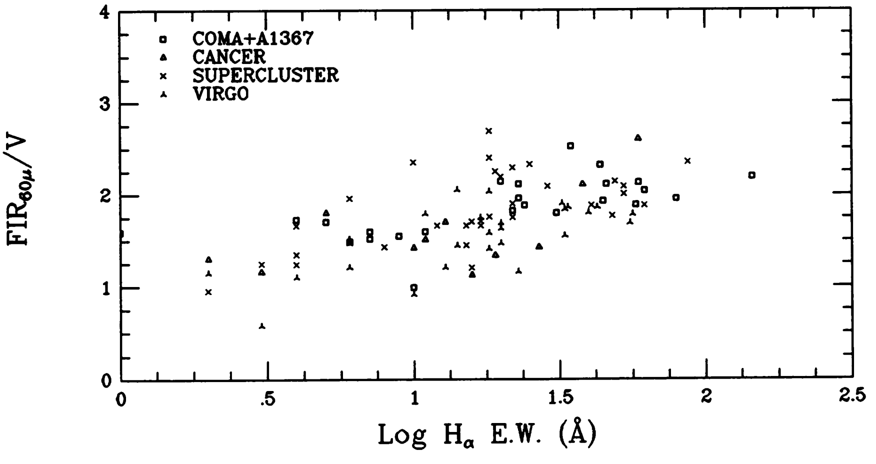

Fig. 3: the relation between the FIR flux (normalized to the flux in the V band) and the H_α E.W.

III. d) FIR emission and environment

To analyze the possible dependence of FIR properties of galaxies on their environmental conditions we construct the FIR (60 μ) to optical luminosity function using the technique of Hummel (1981), which allow us to properly treat upper limits as well as detections. The differential FIR/optical luminosity functions obtained for each individual cluster are plotted in Fig. 4. In each panel the luminosity function obtained for the isolated subsample in the Coma supercluster is also given for comparison. The data indicate that galaxies in clusters have their FIR/optical luminosity functions not distinguishable from those of isolated galaxies. The most obvious interpretation of this result is that the global star formation process in spiral galaxies is not significantly altered by the cluster environment (cf. Bicay and Giovanelli, 1987).

III. e) Radio continuum emission and star formation

Similarly to what discussed in Sect. III c) we analyze the relation between the radio continuum emission normalized to the V band flux and the H_α equivalent width.

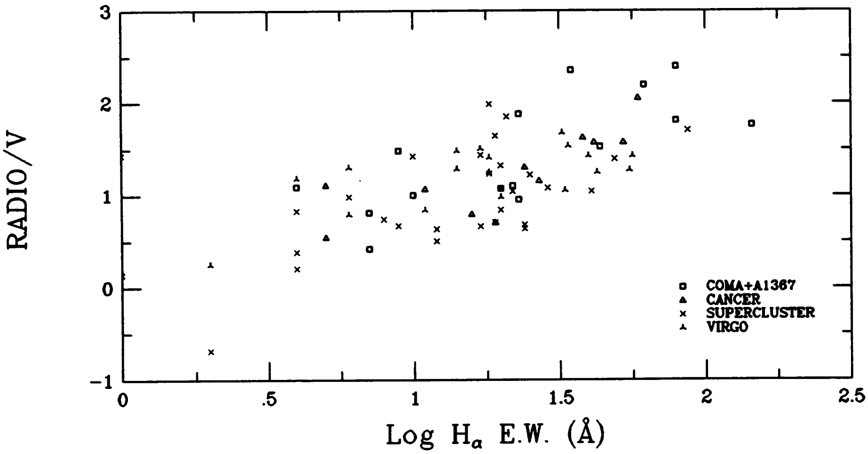

Fig. 5: the relation between the radio continuum emission normalized to the V band flux and the H_α E.W.

As compared to the FIR we find an even tighter correlation between the plotted quantities. The data in Fig. 5 indicate a regression with a slope of one: i.e. a direct proportionality between the radio emission and the star formation rate. This result confirms and reinforces previous similar conclusions (Kennicutt, 1983, Klein,1882, Gavazzi and Jaffe, 1986; Burstein, Condon and Yin, 1987), altogether giving strong support to the idea that cosmic rays electrons are accelerated in galaxies by young, massive stars, most probably in supernova explosions.

III. f) radio continuum emission and environment

Bivariate (radio-optical) radio luminosity functions were already published individually for the 9 clusters analyzed in this work. Gavazzi and Jaffe (1986) compared the radio properties of a sample of relatively isolated galaxies in the Coma Supercluster with those of the two clusters in this region. The most surprising results of their survey was that spirals develop 5 times as strong radio sources in the Coma+A1367 clusters with respect to the isolated galaxies. Similar radio excesses were found in A262 (Fanti et al, 1982) and in A2199 (Gavazzi and Perola, 1980), while normal radio properties were found in Virgo (Kotanyi, 1980), A2197 (Gavazzi and Perola, 1980), A2147, A2151 (Perola and Valentjin, 1979) and the Cancer cluster (Perola et al, 1980).

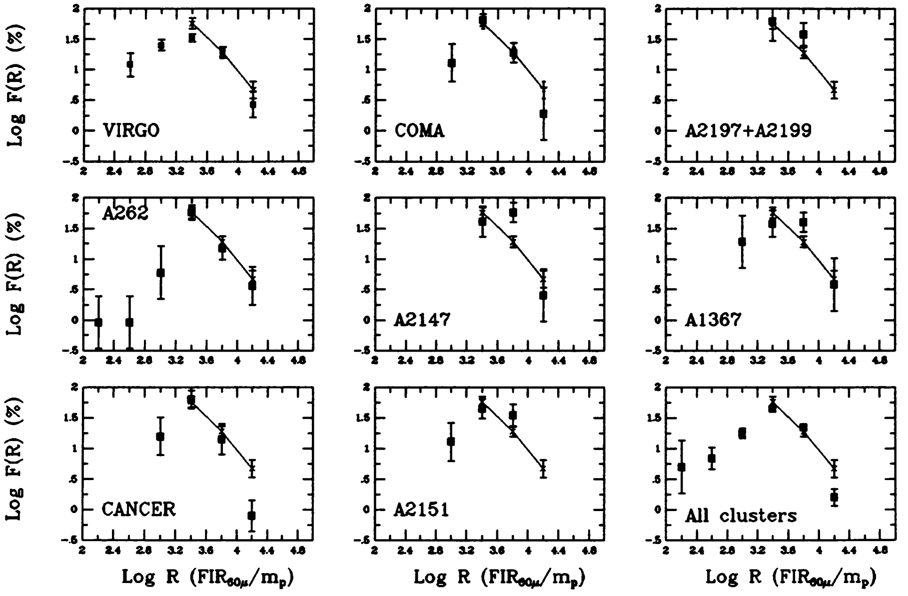

Fig. 4: the differential FIR/optical luminosity functions obtained for each individual cluster and for the isolated galaxies in the Coma Supercluster (continuum line).

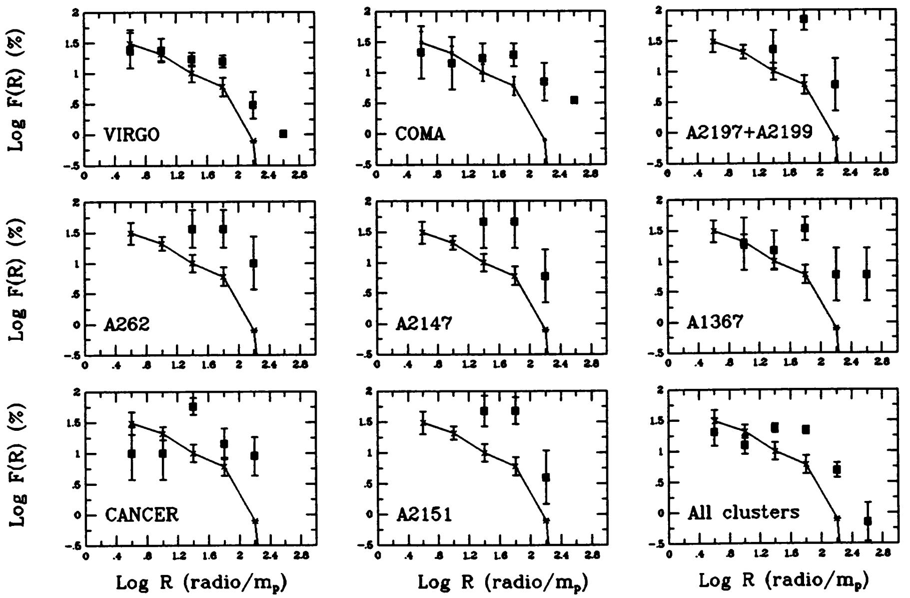

Fig. 6: the differential radio/optical luminosity functions obtained for each individual cluster and for the isolated galaxies in the Coma Supercluster (continuum line).

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Here we redetermine the radio luminosity functions using strictly identical data analysis criteria to identify possible differences between the 9 clusters. The method, similar to the one presented in Section III. d) for the FIR analysis, is based on the determination of the radio to optical luminosity function. The use of the (distant independent) radio to optical ratio R allows to treat together galaxies of different distances and of different optical luminosities. The differential radio/optical luminosity functions obtained for each individual cluster are plotted in Fig. 6. In each panel the luminosity function of the isolated subsample in the Coma supercluster is also given for comparison. The data indicate that galaxies in all clusters tend to have stronger radio/optical luminosities than isolated galaxies. The Virgo and the Cancer cluster, however have marginal excesses, as found by Kotanyi (1980) and by Perola et al (1980). The two Hercules clusters appear as well overluminous with respect to the isolated sample, contrary to what was found by Perola and Valentjin (1979) who probably did not have a proper comparison sample. In particular Fig. 6 indicates that the fraction of cluster galaxies with radio/optical ratio R> 1.8 is about 5 times higher in each bin as compared with the isolated sample.

In conclusion the data indicate that spiral galaxies in clusters have their radio emission (per unit visible light) enhanced by a factor of about 5 with respect to isolated galaxies. The highest radio/V excesses in cluster galaxies occour at positive but small values of HI deficiency. Conversely the minimum values occour at the highest HI Def (probably corresponding to galaxies in which the star formation has been strongly quenched by gas-stripping) as well as at HI def ≤ 0. These are unperturbed cluster objects which have their Radio/V similar to isolated galaxies. These results suggest that enhanced radio continuum activity in cluster galaxies might be induced in those objects which experience the hostile cluster environment from a time sufficient to produce some HI ablation, but short compared with the evolution time scale, in other words in objects that have entered the cluster only recently. Examples of objects of this kind having strong radio/V excess and moderate HI deficiency were found by Gavazzi (1989) in A1367 and in the Coma cluster.

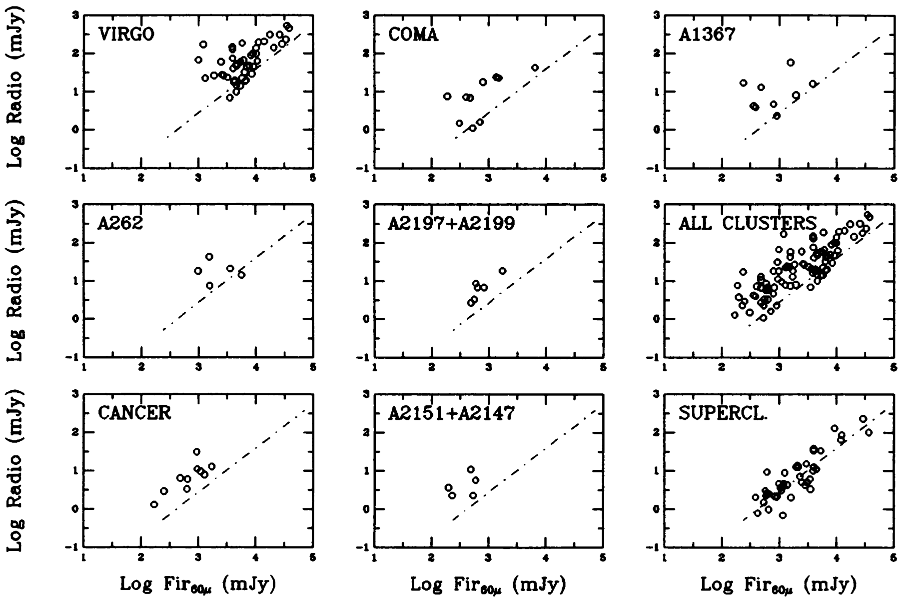

Fig. 7: the relation between Radio continuum and FIR fluxes in the surveyed clusters and in the isolated sample (broken line).

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High resolution HI mapping (Dickey and Gavazzi, 1990) confirmed that these objects have been suffering from stripping for a time sufficient to produce strong dissimetries in the HI distribution, but not to produce a global HI deficiency. The fact that these cluster objects develop abnormally luminous radio sources, given their star formation rate, can be enphasized by plotting the well known relation between Radio and FIR fluxes separately for the clusters and for the isolated samples (Fig. 7). The two samples follow quite different correlations, with the cluster objects being overluminous in the radio at any given FIR with respect to the isolated ones. It is tempting to conclude that the cluster objects have their synchrotron emission enhanced by magnetic field amplification consequent to the dynamical interaction with the IGM.

REFERENCES

Bicay, M. and Giovanelli, R., 1987, Ap.J. 321, 645

Burstein, D., Condon, J., and Yin, Q., 1987, Ap.J., 315, L99

Devereux, N., and Young, J., 1990, Ap.J. 350, L25

Dickey, J., and Gavazzi, G., 1990, Submitted to Ap.J.

Donas, J., Buat, V., Millard, B., Laget, M., 1990, A.A, in press

Fanti, C., Fanti, R., Feretti, L., Ficarra, A., Gioia, I., Giovannini, G., Gregorini, L., Mantovani, F., Marano, B., Padrielli, L., Parma, P., Tomasi, P., and Vettolani, G., 1982, A.A., 105, 200

Gavazzi, G., and Perola, C., 1980, A.A., 84, 228

Gavazzi, G., and Jaffe. W., 1986, Ap.J., 310, 53

Gavazzi, G., Cocito, A., and Vettolani, G., 1986, Ap.J., 305, L15

Gavazzi, G., 1988, in:"The MInnesota Lectures on Clusters of Galaxies and Large-Scale Structure", Ed.J.Dickey, PASP, p.115

Gavazzi, G., 1989, Ap.J., 346, 59

Giovanelli, R., and Haynes, M., 1985, Ap.J., 292, 404

Guideroni, B., 1987, A.A., 172, 27

Gunn, J., and Gott, J., 1972, Ap.J., 176, 1

Haynes, M., Giovanelli, R., and Chincarini, G., 1984, Ann.Rew.Astron.Astrophys, 22, 445

Hummel, E., 1981, A.A., 93, 93

Kenney, J., and Young, J., 1989, Ap.J., 344, 171

Kenney, J., 1989, Proc. II Wyoming conference:"The ISM in Galaxies". ed. H. Thronson and M. Shull

Kennicutt, R., 1983, A.A., 120, 219

Kennicutt, R., 1989, Ap.J., 344, 685

Klein, U., 1882, A.A., 15, 42

Kotanyi, C., 1980, A.A.Suppl., 41, 421

Lonsdale-Perrson, C., Helou, G., 1987, Ap.J., 314, 513

Nulsen, P., 1982, M.N.R.A.S., 198, 1007

Perola, C., and Valentjin, E., 1979, A.A., 73, 54

Perola, C., Tarenghi. M., and Valentyin, E., 1980, A.A., 85, 245

Schmidt, M., 1959, Ap.J., 129, 243

Seiden, P., 1983, Ap.J., 266, 555

Stark, A., Knapp, G., Bally, J., Wilson, R., Penzias, A., and Rowe, H., 1986, Ap.J., 310, 660

Sullivan, W., Bothun, G., Bates, B., and Schommer, R., 1981, A.J., 86, 919

Young, J., 1989, Proc. II Wyoming conference:"The ISM in Galaxies". ed. H. Thronson and M. Shull

Zwicky, F., et al, 1961-1968: "Catalogue of Galaxies and Clusters of Galaxies". Pasadena: California Institute of Technology Press.

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