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STAR FORMATION IN A SAMPLE OF INTERACTING GALAXIES

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ABSTRACT

Optical long-slit spectroscopy is presented for a sample of interacting galaxies mostly from the lists by Vorontsov-Velyaminov. The galaxies were chosen to span a large range of characteristics regarding the morphological types and their mutual distances in the systems. Our results were compared with samples of field galaxies which were first cleaned from interacting objects. We find that star formation is significantly enhanced in nonisolated objects. The induced star formation preferentially occurs in the central regions of the affected galaxies.

We found a high fraction of the analyzed galaxies to be of the LINER type. This could be due to the low level at which this activity is present, which makes it difficult to detect in survey works.
Subject headings: galaxies: interactions — stars: formation

I. INTRODUCTION

The importance of the study of interacting galaxies was first pointed out by Vorontsov-Velyaminov (1959, 1977) with the publication of the Atlas of Interacting Galaxies and also by Arp (1966). The advent of the *Infrared Astronomical Satellite* (*IRAS*) put this question on a new basis. The *IRAS* data have revealed the presence of bursts of star formation even there where it was hitherto hidden at optical wavelengths by large amounts of dust. The relationship between star-formation enhancements and gravitational interaction has been established by many authors (see Kennicutt *et al.* 1987 and references therein).

It has been suggested that gravitational interaction can induce a global instability in a galaxy, which triggers molecular cloud infall into the nucleus, where finally a burst of star formation is produced. Observational evidence for this is given by Mirabel and Sanders (1987) and by Bushouse (1987), who showed respectively that the H_2 and Hα emissions in luminous IR galaxies and in strongly interacting galaxies are concentrated toward the nucleus. Solomon and Mooney (1987) have also suggested that the star formation in interacting objects does not follow the Schmidt law (star-formation rate is correlated with gas surface density), since the ratio L(FIR)/L(CO) in these galaxies is higher than for any galactic molecular cloud [L(FIR) is far-infrared luminosity and L(CO) integrated CO emission]. On the other hand, Kennicutt *et al.* (1987) have concluded from the analysis of a complete sample of interacting galaxies that star formation is not dominantly formed in the nuclear regions being important all over the whole galaxy. These results could mean that the star-formation processes induced by the interaction strongly depends on the properties of the involved galaxies or the type of interaction or both. Alternatively, since the interaction time scale is significantly longer than the lifetime of a burst of star formation, the properties can be very different depending on the phase of the interaction.

After both the observational results and the model calculations it seems that a critical parameter is the gas content and its distribution in interacting galaxies (Norman 1987). But one has also to consider that once the star formation has started, the surrounding medium is rapidly ionized, thus stopping the process. It can also be stopped by some dynamical reactions of the involved galaxies like the apparition of density waves which are known incapable of inducing strong star formation (Elmegreen and Elmegreen 1987).

In any case, it seems necessary first to firmly establish the phenomenology of the whole process. To contribute to this point we present here long-slit spectroscopic data for a sample of interacting galaxies. Our first aim was to compare their global properties and the spatial distributions of the star formation in them in relation with the general properties of each galaxy. We have also compared our results with the properties of isolated objects. The present work is concerned with these points. In a forthcoming paper we will present the analysis of the properties of elliptical galaxies involved in interaction processes and how the dynamical properties are related with the perturbation and with the onset of the star formation.

II. SAMPLE SELECTION AND OBSERVATIONS

a) The Observed Sample

The sample contains 10 groups (24 galaxies), one known merger (NGC 6240), and four isolated Sb galaxies, of which NGC 7177 also turned out to be a merger (see § III*c*). Groups with very different separations between their members and galaxies of various morphological types are included. Two of them, VV 343 and III Zw 55, contain a Seyfert galaxy and have been analyzed in a separate paper (Laurikainen and Moles 1988), but are also included here for the discussion of the data. Five of the groups (Arp 78, III Zw 55, VV 5, II Zw 12, and VV 143) are just binary systems, four of them (Arp 169, VV 343, VV 84, and VV 181) are triple systems and two are mergers, including NGC 6240 and NGC 7177. NGC 275 in VV 81 is a very disrupted object, possibly composed of four different galaxies. Nine of the 11 groups show star-formation activity in at least one of the galaxy members, evidenced by the presence of emission lines.

b) Comparison Samples

In addition to the observed isolated galaxies, two samples from the literature were considered. Prior to the comparison the control samples were reexamined for possible interacting galaxies using the Palomar Sky Survey plates. The isolation criterion for a given galaxy was the absence of companions within seven projected galaxy diameters and with a redshift difference smaller than 700 km s^{-1}. One comparison sample considered was a field galaxy sample by Kennicutt and Kent (1983) without the Virgo Cluster galaxies, which are particularly deficient in gas (Quiderdoni 1987). As a result of our checking only 42 out of the 115 galaxies in the initial list were found to be isolated, and 36 turned out to be interacting systems. The remainder contains galaxies of the Virgo Cluster or with unknown redshift.

For comparison of the nuclear data a complete sample of field galaxies by Keel (1983) was also considered. After reexamination with the same criteria as before, it was reduced to 34 isolated members.

c) Observations and Data Reduction

Long-slit spectrophotometry for the galaxies in the sample was obtained on the nights of 1985 September 10, 11 and 12, with the 2.5 m Isaac Newton Telescope at the Observatorio del Roque de los Muchachos in La Palma in Spain. The 235 mm focal length camera of the intermediate dispersion spectrograph (IDS) with a 300 groves mm^{-1} grating and the image photon counting system (IPCS) were used. With this configuration the spectral range covered by the spectra was $\lambda\lambda$3300–7000 and the resulting spectral resolution 5 Å (FWHM). Seeing conditions were good during the three nights, most of the time between 0".8 and 1".1, and the spatial resolution achieved was about 2". The slit was positioned to cover two galaxies in each exposure, except for some cases where it was oriented along the major axis of a given galaxy. The log of the observations is given in Table 1.

Data reduction was carried out using the SPICA package with the VAX 11/750 of the Instituto de Astrofisica de Andalucia. For the absolute flux calibration two standard stars from the Oke (1974) list were observed each night. To correct for the second-order effects in the spectra of the standard stars they were observed with and without the color filter GG 385 and were then combined to get the whole calibration curve. For the first two nights the flux calibration was accurate within 20% and 12%, respectively. For the third night it was not possible to get so accurate a calibration since the two observed standard stars gave too different calibration curves. We could verify, however, that the calibration curves for the two first nights and for one of the standard stars in the third night are similar and used in this form to calibrate the data of the last night. The zero-point error for it estimated from the calibration of the standard stars is estimated to be of 50%.

III. RESULTS

a) Characterization of the Nuclei

For the galaxies with emission lines in the central regions the nucleus was defined from the emission-line intensity distribution along the slit, and the exponentially decreasing part of the profile was considered as the nucleus. This definition is straightforward when the emission lines are strong, but uncertain for the galaxies where the lines are weak.

Before describing the nuclear spectroscopic properties, great care was taken to correct for reddening. We adopt the case B recombination values of the Balmer decrement for low densities and 10,000 K for all the nuclei. This would not be exactly

TABLE 1

OBSERVATIONS

Galaxy	Other Name	Morphological Type	Date	P.A.	Exp. time (s)	Slit width [μm]
NGC 772	Arp 78, U1466/1464	S(s)b	1985 Sep 10	330°	1400	260
NGC 770	...	E		330	800	260
NGC 7236/7237	Arp 169, III Zw 172, 3C 442, Zw 469, U11958	S0/S0	1985 Sep 10	314	2500	200
				314	1200	200
NGC 1409/1410	III Zw 55	S0/E	1985 Sep 10	20	1500	260
NGC 7674/H96C	VV 343, Arp 182	S(r)bc/	1985 Sep 10	67	1500	260
NGC 7675				67	1500	260
NGC 7606	...	S0		67	600	260
	...	Sb	1985 Sep 10	314	350	200
				314	600	500
NGC 6240	4C02·44, VV 617, U10592	Irr	1985 Sep 11	31	1500	200
NGC 7436a, b	VV 84, U12269	E/	1985 Sep 11	90	1000	200
NGC 7435	U12267	SBa		342	1800	200
NGC 1587/1588	II Zw 12, Mrk 616, U3063/3064	E/E	1985 Sep 11	260	1500	260
NGC 7177	U11872	SABb	1985 Sep 11	35	1300	200
NGC 7752	VV 5, Arp 86	Irr	1985 Sep 11	360	1600	260
NGC 7753	IV Zw 165	S(rs)bc		55	500	260
				90	1600	260
NGC 274/275	VV 81, Arp 140	S0/S(rs)cd	1985 Sep 12	320	1800	260
NGC 275	...			240	1800	260
A236 18A/B	Arp 258, VV 143	Irr/SBOa	1985 Sep 12	211	1600	260
NGC 7578/A/B/C	VV 181, Arp 170	S0/E	1985 Sep 12	360	400	200
A/C	U12477/12478			360	1500	200
B	...			340	1200	200
NGC 7723	...	SB(r)b	1985 Sep 12	61	1200	300
NGC 488	...	S(r)b	1985 Sep 12	211	600	260

TABLE 2

Observed Line Intensities Relative to Hα for the Strong Lines and Relative to [N II] 6583 for the Weak Lines[a]

Line	NGC 772 Nucleus	NGC 772[b,c] H II-reg.	NGC 7237 Nucleus	NGC 6240[d] Nucleus	NGC 7752[c,e] Nucleus	NGC 7753 Nucleus	NGC 7753[f] H II-reg.	NGC 7435[g] Nucleus
[O II] 3727	...	0.115	0.375	0.143	0.227	...	0.165	0.641
[Ne III] 3869	...	...	...	...	...	...	...	...
He I + H8 3888	...	...	...	...	...	...	...	...
[Ne III] + Hε 3968	...	...	...	...	...	...	...	...
[S II] 4068, 71	...	...	...	...	...	...	...	...
Hσ 4101	...	...	...	...	0.013	...	...	...
Hγ 4340	...	0.046	...	...	0.042	...	0.042	...
Hβ 4861	...	0.150	...	0.054	0.139	...	0.079	...
[O III] 4959	...	...	...	0.035	0.032	...	0.029:	...
[Fe III] 4986	...	...	...	...	...	...	...	...
[O III] 5007	...	...	0.184	0.105	0.095	...	0.059	0.601
[N I] 5199	...	...	...	0.033	...	...	...	...
He I 5876	...	...	...	...	0.019	...	...	...
[O I] 6300	...	...	...	0.273	0.013	...	...	...
[O I] 6364	...	...	...	0.074	0.005	...	...	...
[N II] 6548	...	0.097	...	0.519	0.124	0.554	0.059	...
Hα 6563	0.598	1.00	0.263	1.00	1.00	1.00	1.00	0.572
[N II] 6583	1.00	0.250	1.00	1.558	0.373	1.120	0.320	1.00
[S II] 6717	0.152:	...	...	0.872	0.130	0.330	0.081:	1.09
[S II] 6731	0.244:	...	...	...	0.119	0.260	0.046:	...
log f(Hα)	...	−13.85	...	−13.11	−13.05	−14.17	−13.98	...
EQ(Hα)	1.7	30.4	1.1	76.4	107.0	8.7	86.7	3.6
log f(6583)	−13.85	...	−14.16	...	...	...	...	−11.25
Min error %	3	2	4	1	1	3	1	2
Max error %	14	13	15	3	30	10	24	6
z	0.0079	0.0073	0.0260	0.0238	0.0160	0.0170	0.0165	0.0271
Channel (kpc)	0.116	0.107	0.378	0.347	0.233	0.247	0.239	0.394
$E(B-V)$(Galaxy)	0.06	0.06	0.05	0.09	0.05	0.05	0.05	0.060
$E(B-V)$(internal)	...	0.846	...	1.649	0.722	...	1.315	...
T(spectral)	L	H II	L	L	H II	L	H II	L

[a] Fluxes are in ergs cm^{-2} s^{-1}.
[b] Absorption bands are detected coinciding the Balmer emission lines.
[c] Internal galactic extinction was calculated by the iterative method explained in the text.
[d] [N II] λ6583 was separated from (Hα + N II) blend by Gaussian fit, and [N II] λ6548 flux was calculated theoretically from [N II] λ6583 line flux. The lines Hσ, [Ne III] λ3869, and Hγ, detected by Fosbury and Wall (1979) are considered here too weak to be measured.
[e] Absorption coinciding with the Balmer lines was detected and [S II] λλ6717, 6731 lie in a deep atmospheric band. [S II] lines were measured by fitting an artificial continuum under the lines.
[f] Keel *et al.* (1985) detected [O I] λ6300 line, which we did not see in our spectrum.
[g] Measurements were made after subtracting the continuum of the nearby galaxy NGC 7435. This method is important for [O III] λ5007 line, which lies in a deep MgH absorption band.
[h] For this galaxy sky lines disturb measurements of the lines [O I] λ6300, 6364, and Hα, which effect might be important for the [O I] lines. Absorption coinciding with the Balmer emission lines was detected.
[i] The lines were measured after subtracting the continuum.

true for low-ionization nuclear emission-line regions (LINERs), for which Veilleux and Osterbrock (1987, VO in the following) recommended the value $I(\text{H}\alpha)/I(\text{H}\beta) = 3.1$, based on the hypothesis that LINERs are photoionized by a power-law continuum. In this case, a warm neutral gas component is produced in which case collisional effects could be important (Netzer 1982). On the other hand, different photoionization mechanisms have been proposed to explain the LINER phenomenon (Heckman 1987; Terlevich, Melnick, and Moles 1987) resulting in different values for the Balmer line ratio. In view of all these difficulties the case B recombination Balmer decrement was used to correct all the observed line ratios.

Another effect to consider is the presence of absorptions coinciding with the Balmer emission lines. To correct this effect theoretical models by Diaz (1985) were considered. They are based on the assumption that the photoionization is produced by a recently formed star cluster of solar metallicity and with a Salpeter initial mass function. For the model we chose the absorption Balmer line ratio Hα:Hβ:Hγ = 7:10:10. The value of the absorption coincident with each Balmer emission line and that of the reddening coefficient can be calculated iteratively by the formula:

$$0.135\{\log[2.86(\text{H}\beta + 1.43a)] - \log[\text{H}\alpha + a]\} = -0.335\{\log[0.47(\text{H}\beta + 1.43a)] - \log[\text{H}\gamma + 1.43a]\},$$

where a is absorption correction for Hβ. The values found are given in Table 2.

The corrected line ratios were used for the classification of the nuclear spectra. The diagnostic diagrams by Baldwin, Phillips, and Terlevich (1981; hereafter BPT) have been recently revised by VO who considered only reddening-independent line ratios. Given the small number of well-detected lines in many observed galaxies and the uncertainties on the reddening correction, when both sets of diagrams gave different results, we kept the VO diagnostic. The spectral types are given in Table 2. For some nuclei only the [N II] λ6583 and Hα lines were well detected. For these galaxies a LINER nuclear type was assigned when the nitrogen line was more intense than Hα. They are NGC 772, NGC 7237, and NGC 7435 which also

TABLE 2—*Continued*

NGC 275A[h] Nucleus	NGC 275B[c] Nucleus	NGC 275C Nucleus	NGC 275D[c] Nucleus	A236 18A Nucleus	A236 18B Nucleus	NGC 7723 Nucleus	NGC 7723 H II-reg.	NGC 7177[i] Nucleus
0.434	0.610	1.468	0.899	0.341	0.845	...	...	0.728
0.013	0.041	...	...	0.086	...	...	...	...
0.019	...	...	...	0.045	...	...	...	...
0.018	...	...	...	0.035	...	...	...	...
0016:	0.044	...	0.045:	...	...	...	...	...
0.042	0.045	...	0.047	0.029	...	...	...	...
0.074	0.091	...	0.095	0.078	...	...	...	...
0.029	0.271	0.272	0.274	0.215	...	0.116:	0.202	...
0.125	0.160	...	0.091	0.440	...	...	...	...
0.004	...	...	...	...	...	...	...	...
0.326	0.488	0.285	0.271	1.293	0.401	...	...	...
0.005	...	...	...	...	...	...	...	...
0.037	0.031	...	...	...	...	...	...	...
0.011	...	...	0.038	...	...	...	...	...
0.005	...	...	0.074	...	...	...	...	...
0.056	0.044	0.101	0.033:	...	...	0.179	0.098	0.172
1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.160	0.119	0.215	0.196	...	0.411:	0.331	0.234	0.604
0.130	0.090	0.348	0.197	0.057:	0.187:	0.097	0.086	0.470:
0.101	0.077	0.232	0.133	...	0.225:	0.069	0.090	0.211:
−12.72	−13.63	−14.32	−14.01	−14.13	−14.83	−13.12	−14.10	−13.80
299.0	153	17.0	107.0	261.0	19.2	22.2	34.1	130.7
...	...	...	...	...	...	...	...	...
1	1	1	1	1	4	1	1	2
12	7	18	30	13	21	6	12	10
0.0059	0.0054	0.0057	0.0057	0.0135	0.0136	0.0060	0.0060	0.0038
0.086	0.085	0.083	0.083	0.196	0.198	0.087	0.087	0.056
0	0	0	0	0.09	0.09	0	0	0.06
0.480	0.209	0.221	0.236	0.502	...	...	0.484	...
H II	H II	H II/*L*	H II	H II	...	H II	H II	*L*

shows intense [S II] lines. It is worth noting that although NGC 6240 is here classified as LINER, Andresian and Khachikian (1987) have detected two nuclei (see also Fried and Schulz 1983) 2″ apart and with different spectral types, one Seyfert 2 and the other of H II type. We will note that an important fraction (about 50%) of the emission-line nuclei in our sample were classified as LINERs among both early- and late-type galaxies.

NGC 7237 is a particular case showing P Cygni–type Balmer lines in the nucleus. This can be interpreted as a hint for the presence of a Type II supernova (SN), since Niemelä, Ruiz, and Phillips (1985) have shown that at the maximum light curve phase of SN II the Balmer lines show this kind of structure.

b) Global Star-Formation Rates

In general $L(H\alpha)$ and $L(FIR)$ are considered as indicators of recent star formation in a galaxy. The ionization is suggested to be due to the emission of massive OB stars and the far-IR emission reradiation by dust. It is worth noting, however, that $L(FIR)$ does not reflect directly the dust content, but depends also on the dust temperature T_d at a given H_2 mass (Young *et al.* 1986). Temperature T has been found to be 2 times higher for interacting galaxies than for field galaxies (Young 1987). The $L(FIR)$ is thus an index for the presence of "hot" dust in a galaxy. High $L(FIR)$ does not necessarily mean, on the other hand, enhanced star formation in a galaxy. It can be high also if there is a large fraction of stars at the beginning of their formation surrounded by high hot dust masses. Despite these complications $L(H\alpha)$ and $L(FIR)$ can give good approximations of relative star-formation rates, when interacting and field galaxies are compared. It is noticeable that a large fraction of the sample galaxies are LINERs, which are not usually considered in terms of photoionization by OB stars. This is not excluded, however, and different efforts have been made to reduce them to star-formation processes (Diaz 1985; Heckman, Armus, and Miley 1987, hereafter HAM). In the following, Hα and far-IR properties of galaxies with LINER–type nuclei are considered as indicators of star-formation activity.

Far-IR and Hα luminosities have been converted to star-formation rates by using the formulae given by Hunter *et al.* (1986) and Hunter and Gallagher (1986), respectively, adopting a Salpeter initial mass function (the value of the Hubble constant $H_0 = 100$ km s^{-1} Mpc^{-1} is used through this work):

$$\mathrm{SFR}(H\alpha) = 7.07 \times 10^{-42} L(H\alpha)\, M_\odot\ \mathrm{yr}^{-1}$$

$$\mathrm{SFR}(FIR) = 1.34 \times 10^{-34} L(FIR)\, M_\odot\ \mathrm{yr}^{-1}\ .$$

The luminosities and star-formation rates for the galaxies are given in Table 3. FIR fluxes were taken from the *IRAS* Point Source Catalog. The Hα related parameters were calculated using the integrated Hα fluxes (global parameters) corrected for Galactic extinction. It is assumed that Hα flux is radially symmetric with respect to the center, and the information along the slit is representative throughout the galaxy, which is a good approximation for all the sample galaxies except for NGC 772 for which this method was not applied. In Table 3 we give the star-formation rates normalized to the surface area of the whole galaxy and to that of the emission-line region as they appear in the slit. To take into account the large aperture used in the far-IR observations we compared the

TABLE 3

Hα AND FIR DATA

Galaxy (1)	log Hα (2)	log Hα (3)	log SFR/A (4)	log SFR/ESE (5)	SFR(global)/SFR (nuclear) (6)	f(60 μm)/ f(100 μm) (7)	log L(FIR) (8)	SFR(FIR)/ SFR(H_α) (9)	log SFR/A (10)	log SFR/ESE (11)	SFR(FIR)/ SFR(H_α) (12)
NGC 772	38.91					0.230	43.51				
NGC 6240	41.43	41.69	−7.813	−7.034	0.049	0.897	44.84	26.52			
NGC 7752	41.14	41.16	−6.775	−6.775	0.474]⁻	0.479]⁻	43.93]⁻	9.18	−5.791	−5.791]⁻	1.695
NGC 7753	39.46	40.54	−8.651	−6.493	0.021]				−7.716	−5.558]	
NGC 275/A	40.48	40.98	−6.886	−6.729	0.171]⁻	0.531]⁻	43.03]⁻	1.46	−6.464	−6.305]⁻	1.234
NGC 275/B/C/D	40.49	40.61	−7.478	−7.123	0.031]				−7.270	−6.941]	
NGC 1410	41.00	41.00	−7.512	−6.721	0.161	0.430	43.55	6.74			
NGC 7674	41.82	41.92	−7.258	−6.874	0.058]⁻	0.668]⁻	44.43]⁻	5.61			
H96/c	40.80	40.80	−7.667	−6.907	0.174]						
NGC 7177	38.66	39.34	−8.264	−7.007	0.042						
NGC 7435	43.58	43.58	−5.005	−3.857	0.071						
NGC 7273	38.64	38.64	−10.352	−8.954	0.040						
A236 18A	38.91	39.10]⁻	−8.187]⁻	−7.726				]⁻	−7.721]⁻	−7.260	
A236 18B	39.43	39.43]									

Col. (1).—Galaxy identification by NGC, Hickson, or Arp atlas number.

Col. (2).—Logarithm of the integrated Hα nuclear luminosity, in ergs s^{-1}, corrected for Galactic reddening only.

Col. (3).—Logarithm of the integrated global Hα luminosity, in ergs s^{-1}, corrected for Galactic reddening. In cols. (4), (5), (6), and (9) star formations are calculated by using Galactic extinction corrected values for luminosities.

Col. (4).—Logarithm of the global star-formation rate (SFR) per unit area A, in M yr^{-1} pc^{-2}, derived from Hα luminosity.

Col. (5).—As in the previous column, but normalized to the emission-line surface area (ESA) of a galaxy.

Col. (6).—Global to nuclear star-formation rate.

Col. (7).—Dust temperature $f(60\ \mu m)/f(100\ \mu m)$.

Col. (8).—Logarithm of the far-IR (FIR) luminosity, in ergs s^{-1}.

Col. (9).—Far-IR to Hα star-formation rate. The latter is calculated by using the integrated global luminosity of Hα for the interacting galaxy pair, if both galaxies manifest activity in them.

Cols. (10)–(12).— As columns (4), (5), and (9), respectively, but Hα luminosities are corrected both for Galactic and for internal galactic extinction.

far-IR luminosities with the total Hα luminosity of all the closely interacting components.

If no systematic variation in the spatial Hα/Hβ distribution was found, the internal extinction corrected values are given also in Table 3. For NGC 7753 internal reddening cannot be determined, but it is considered to be of the same amount as for NGC 7752 which is probably a lower limit, since extinction in an outer H II region of this galaxy is higher than for the nucleus.

Global star-formation rates normalized to the galaxy surface area for the galaxies in our sample (see Table 3 col. [4]) are systematically higher than for field galaxies. They also appear higher than average for interacting disk galaxies found by Bushouse (1987; see Fig. 1 in Bushouse; notice the different value for the Hubble constant used by him). When the data are normalized to the emission-line surface area (Table 3, col. [5]) the dispersion in the star-formation rates is considerably reduced. Particular cases are NGC 7237 and NGC 7435 at the low and high ends of the distribution, respectively. It is worth noticing that for galaxies in a group for which internal extinction could be corrected, the star-formation rates normalized to the emission-line region (Table 3, col. [11]) are not very different from one galaxy to an another.

The infrared excess [SFR(FIR):SFR(Hα)] (Table 3, col. [9]) for most of the sample galaxies is as high as typically found for interacting galaxies (see Bushouse) with the exception of the group VV 81, for which there is no excess, while it is very high for NGC 6240.

c) Extranuclear Emission

Off-nuclear emission was clearly detected in NGC 772, NGC 7674, NGC 6240, and in NGC 7177. The extended emission appears to be asymmetrically distributed with respect to the nucleus. NGC 7674 has a well-known Seyfert 2 nucleus and has been discussed in an earlier paper (Laurikainen and Moles 1988). Its extended emission was attributed to recently born stars.

NGC 7177 is an isolated galaxy with some emission over the disk. The optical light and emission-line intensities are asymmetrically distributed, having two maxima which we interpret as evidence for merging. On the side where the companion has been detected, the extinction seems to be more important than on the other side.

NGC 772 has a very large extended emission-line region on one side of the galaxy, classified as low-excitation H II region type, whereas NGC 6240 has disk emission on the two sides of the center being more pronounced to the northeast than to the southwest. The off-nuclear spectrum of NGC 6240 presents all over the slit intense low-ionization lines. NGC 6240 is discussed by HAM as an example of a LINER where the activity is induced by star-burst driven winds.

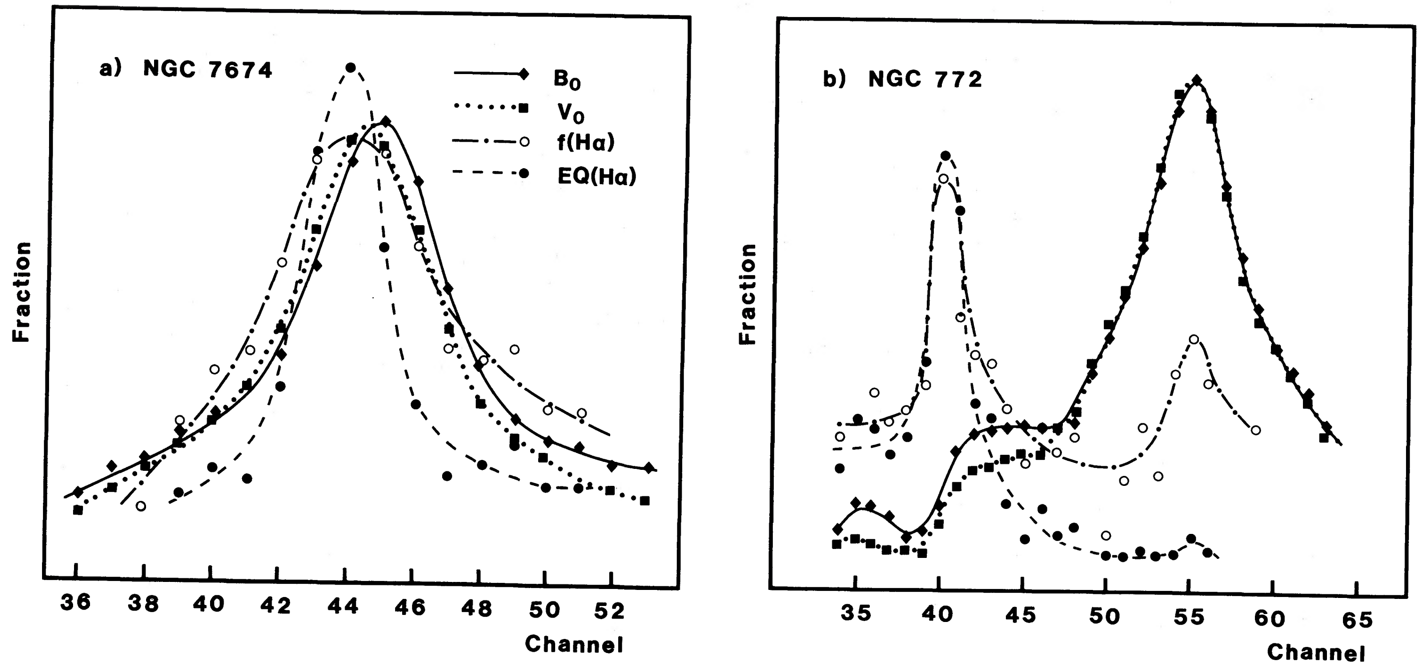
NGC 7752 shows emission lines throughout the whole detected galaxy, but in this case it is somewhat misleading to speak about extended emission, since the galaxy is rather compact. It is worth noting, however, that the spatial optical intensity distribution and also the emission-line intensity distribution in this galaxy are asymmetrically distributed being slightly extended to the direction opposite to the position of the main galaxy.

All the studies of interacting galaxies (Bushouse 1987; Kennicutt *et al.* 1987; Hummel 1981) seem to indicate that the nucleus is more sensitive than the disk to the effects of galaxy interactions. It is less clear whether the "main" Hα luminosity in interacting galaxies is emitted by the nucleus or by the disk. In this work we find that $[SFR(H\alpha/A)]_G/[SFR(H\alpha/A)]_N \ll 1$ for all those galaxies for which this parameter could be determined, which means that star formation in these galaxies is mainly nuclear in origin. This result is in agreement with Bushouse (1987) for strongly interacting galaxies. The nuclear Hα luminosity is typically 30%–100% of the total, which is much more than was suggested by Kennicutt *et al.* (1987) and Hummel (1981). They found that only 13%–33% of the Hα luminosity is emitted on average by the nucleus in interacting systems. The difference between these results possibly arises from the fact that galaxies studied by Kennicutt *et al.* and Hummel were involved in less severe interactions and therefore "shifting" of star-formation activity from the disk to the nucleus was not as pronounced as in samples of more violently integrating galaxies.

To analyze the localization of the star-forming regions with respect to the distribution of older star populations we compared different indices measured on the slit. First, the Hα line intensity distribution along the slit localizes the very recent star-formation regions. The distribution of the equivalent width EW(Hα) gives, on the other hand, the distribution of the star-formation sites with respect to the old G and K giants. Finally, the *B* and *V* colors are essentially contributed by stars of intermediate age. We measured these indices for the galaxies in the sample from the information on the slit. The results are illustrated in Figure 1 for three galaxies. NGC 7674 is representative of the whole sample with the exceptions of NGC 7177 and NGC 772. For the latter the results are also shown. NGC 7723 is an example of a field galaxy. The emission-line fluxes were obtained by using a system where for a dereddened line and its continuum the same wavebands were measured in every channel. This method made the measurements comparable in the slit. The *B* and *V* magnitudes were measured by integrating over Johnson's color bands.

In general, the luminosity indicators have the same spatial distribution. This result is in agreement with those obtained by Hodge and Kennicutt (1983) who found that the radial distribution of the star-forming regions in isolated spirals follows the integrated light distribution of the stellar disk. Young (1987) also found for NGC 6946 that CO correlates in radial distribution with the Hα, radio, and optical emissions. However, the distribution of the EW(Hα) is not flat but decreases in general from the nucleus outward. Bushouse found the same result, which he interpreted as difference in the patterns of the preinteraction and interaction-induced star-formation activity. The last takes place preferentially in and around the nuclear regions. However, one can think about an alternative interpretation considering that the EW(Hα) is very sensitive to the age of the newly formed star cluster. Then the spatial distribution of that indicator could be due to the different ages of the ionizing star clusters. Intuitively it looks as if the star formation induced by the gravitational interaction would propagate from the outer parts toward the nucleus.

Small differences of about 0.7–1.6 kpc between the maximums of EW(Hα) on the one hand, and the rest of the indices on the other hand, are noticed for NGC 6240 and for VV 81, but these shifts are in the limits of the spectral resolution. Exceptions to this general tendency are NGC 7177 and NGC 772. In NGC 7177 formation of young stars with respect to the old star population is more pronounced on that side of the galaxy where the extended emission was detected, the colliding galaxy component staying on the opposite side of this region.



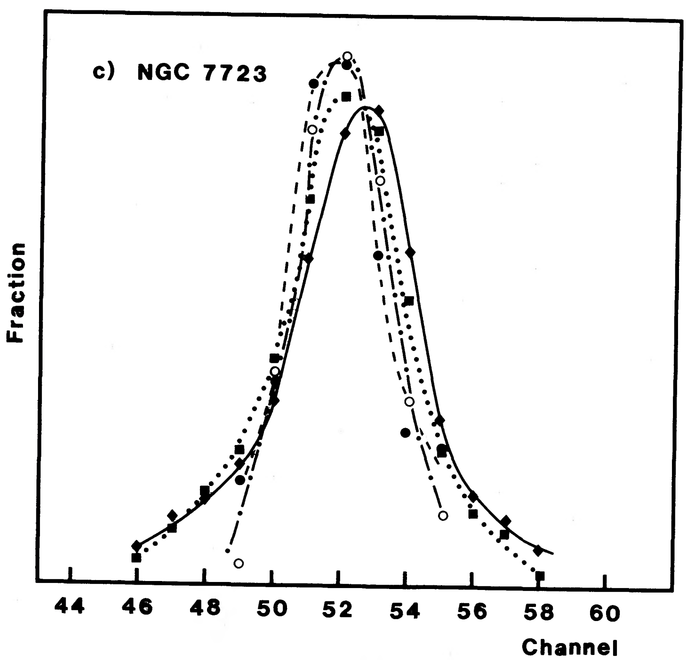


FIG. 1.—Spatial distributions of V and B band magnitudes, Hα fluxes, and equivalent widths (EQ) of Hα for the interacting galaxies (*a*) NGC 7674, (*b*) NGC 772, and (*c*) for the field galaxy NGC 7723. The intensities are normalized by constant to be representative in the figure.

The main flux of the nucleus of NGC 772 is emitted at all wavelengths by the same regions, but in the off-nuclear zone the main Hα luminosity originates from a different region than the rest of the luminosity.

The excitation state for NGC 6240 and NGC 7752 is relatively low, about 0.3, and does not change considerably along the slit, whereas it decreases gradually from the central part toward the edge of a galaxy in the A, B, and C components of VV 81.

d) Dependence of Star Formation on Galaxy-Galaxy Interaction

Evidence indicating that galaxy-galaxy interactions "often" induce strong activity in galaxies has been reported by several authors (HAM; Joseph and Wright 1985; Cutri and McAlary 1985; Bushouse 1987; Houck *et al.* 1985). Most of the studied samples contain morphologically disrupted systems or high far-IR luminosity objects which appear to be strong interacting objects. Using differently selected samples Hummel (1981) and Kennicutt *et al.* (1987) have questioned this interpretation. They found that "most" of the interacting galaxies have similar star-formation activity as field galaxies and that strong star bursts are rare.

The relevance of gravitational interaction on star formation is studied here by reexamining the $L(\mathrm{FIR})/L(B)$ number distributions of the field galaxy samples by Kennicutt (1983) and by Keel (1983), once the interacting candidates were excluded as explained in § II. We found that the secondary maximum in the $L(\mathrm{FIR})/L(B)$ histogram of Keel's original sample was essentially due to the consideration of interacting systems (see Fig. 2). On the other hand, among the interacting systems of this sample the fraction of non or mildly star-forming galaxies does not completely disappear. The same conclusion can be made for the "field" galaxy sample by Kennicutt. Considering that most of the interacting galaxies in the histogram appear at the secondary maximum or after that (see Fig. 11 in Kennicutt *et al.* 1987), it can be concluded that gravitational interaction induces star-formation activity in "most" of the interacting systems. Note that the difference in the $L(\mathrm{FIR})/L(B)$ scale between Kennicutt *et al.* and this work is possibly due to the different ways of calculating $L(B)$ luminosities, which in this paper were calculated through solar quantities. One should be careful since this L_B is more than a factor of 4 larger than the flux in the B bandpass (see Hunter and Gallagher 1987). Kennicutt *et al.* did not define their way of calculation.

V. DISCUSSION

Kennicutt and Keel (1984) have compared the samples of interacting and field galaxies and found that the fraction of

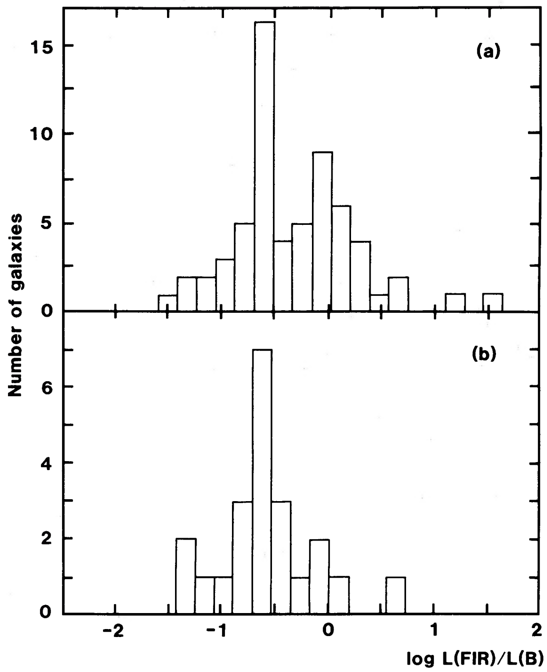


FIG. 2.—Number histogram of total far-IR luminosity normalized to total blue luminosity (*a*) for Keel's (1983) complete sample of "field" galaxies and (*b*) for the "real" field galaxies of the same sample after eliminating interacting galaxies.

LINERs is significantly smaller among interacting objects. Thus it is surprising that most of the galaxies studied here are LINERs. The LINERs we found are all low-level active objects and none is a strong *IRAS* source, except for NGC 6240. Therefore they cannot be related to the high-IR luminosity LINERs found by HAM among possible mergers and closely interacting galaxies. Sadler (1987) has argued that the LINER activity may be a typical phenomenon in all normal early-type galaxies, but we note that most of the galaxies in our sample are spirals. To solve the discrepancy between the results by Kennicutt and Keel and this work, we can think about two possible explanations. The first one is simply that low-level activity objects like those detected here can be unnoticed in survey works. The other one could be that we have eventually selected systems in the later phases of the interaction process and only low-level activity can manifest.

On the other hand, the LINER activity could embrace different physical mechanisms as stressed by Heckman (1987). In spite of this we found, however, that the far-IR and the Hα luminosities are strongly correlated for all the galaxies in our sample. The slope of the $L(\mathrm{H}\alpha)$–$L(\mathrm{FIR})$ relation is essentially the same for field and interacting objects, except for the strong *IRAS* sources considered by HAM (see Fig. 3). Therefore, a unique mechanism could be the main source of energy production in Hα and FIR fluxes in all galaxies. A good example is VV 5, which apparently shows high far-IR excess, probably from star formation, which disappears when the Hα luminosity is corrected for internal extinction.

One common result in all studies of star formation in interacting galaxies is that it is enhanced with respect to what is observed in isolated systems. Comparison is, however, problematic as stressed by different authors (see Lequeux 1986). An important point in this respect is the nature of the initial mass function (IMF). In general, it is considered as universal, but the results can be interpreted either as an enhanced star-formation rate or as a preferential formation of massive stars (Dostal 1982). Larson (1981) has argued that the IMF for a given galaxy could be related with the conditions of its local environments. On the other hand, Terlevich (1982) has pointed out that the slope of the IMF might decrease with decreasing metallicities and consequently the IMF could depend on the evolutionary stage of the galaxies. Finally, the properties of the molecular gas distribution can be deeply modified during the interaction.

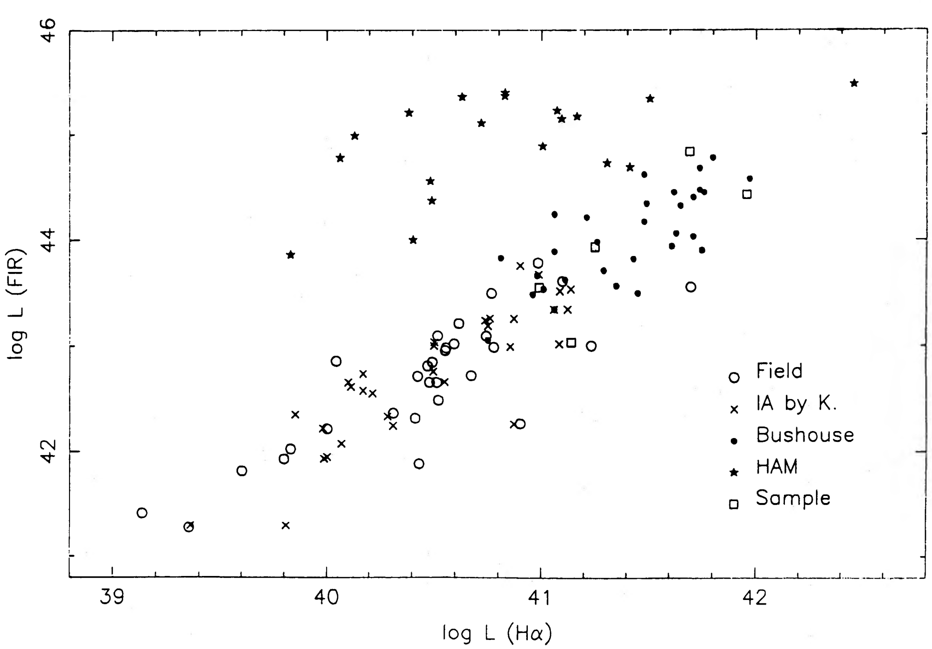


FIG. 3.—Far-IR luminosity. Open circles are "real" field galaxies by Keel (1983), crosses interacting galaxies of the same sample, filled circles and stars interacting galaxies by Bushouse (1987) and HAM, respectively, and quadrant galaxies of our sample.

In spite of these warnings, Hα and *IRAS* data are generally interpreted as showing an enhanced star formation in interacting galaxies. It is worthwhile to mention here in support of this view the color effect in gravitationally bound galaxies, known as the Holmberg effect, which is a color correlation between the components in a binary galaxy (Holmberg 1958; Madore 1986). The effect is also present in our sample for the groups VV 143, VV 5, and VV 343. Related to this is the fact that in some cases the star-formation enhancement is seen in only one of the components of the system. Analyzing galaxies from the Atlas of Peculiar Galaxies (Arp 1966), Joseph (1987) found that in no case does more than one member of a pair exhibit enhanced star formation. This result is found for three systems (Arp 169, VV 84, and III Zw 55) in our sample, in which the quiet member is an early-type galaxy, so the reason can be small gas content. One explanation of the difference between the results by Joseph and this work can be that our galaxies have stayed longer in the interaction phase. Then if one assumes some evolutionary sequence between H II and LINER or Seyfert activity (Terlevich and Melnick 1985; Terlevich, Melnick, and Moles 1987), the different ages of the star-formation processes could explain the different result. Evidence for this could be found by the fact that 21 galaxies in Joseph's sample are high-excitation H II type object, four are LINERS, and six Seyferts, whereas low activity level LINERs and low-excitation H II–like galaxies are the dominant ones in our sample. An alternative interpretation is that the difference between the two results is related to dust content. A galaxy could be experiencing relatively high star-formation rates but have normal near-infrared colors, if it contains little dust or the energy source is located in a very small area to the nucleus so that only a little amount of dust is heated. A compact energy source can be distinguished from a more extended source by Wright *et al.* (1988) if there is no extended 10 μm radiation on scales greater than a few parsecs. In this scenario there still remains the problem why all companions of the Joseph sample were poor in dust.

In four systems (Arp 78, VV 5, VV 343, and VV 143) the main galaxy is accompanied by a small satellite. Arp 169 is different from all the others in the sense that the majority of the Hα flux in NGC 772 is emitted by the off-nuclear regions as well as its peculiar distribution with respect to the emission at other wavelengths. This is also the only one of the four groups in which the satellite does not manifest activity at all. Even if the star-formation distribution in NGC 772 is very peculiar, its global properties are similar to those of field galaxies. The dust temperature, 28 K, is even lower than average for isolated spirals (Young 1987), its X-ray luminosity at the 0.5–3.5 keV is the same as that found by Fabbiano (1986) for normal galaxies and its $L(\mathrm{FIR})/L(B)$ ratio is similar to the mean value for isolated spirals. Its H I mass of 19.9×10^9 $M_\odot$ (Roberts 1969) is high, but taking into account its M_B luminosity this is in accordance with the relation found by Shostak (1978) for normal spirals.

Two of the properties of NGC 7752 call special attention. Extinction $c = 1.06$ is very high, but the temperature $T_d = 35$ K is not far from the mean value for normal spirals, and therefore much smaller than that found by Young (1987) for interacting galaxies. One possibility is that NGC 7752 could be a complex where the stars are surrounded by high-density, relatively cool dust. However, it remains difficult to understand why the far-IR luminosity is so high unless the stars produced during the interaction phase are of lower masses than those formed in previous star-formation episodes. This could explain the low dust temperature and the high far-IR luminosity according to the calculations by Lonsdale, Persson, and Helou (1987). This abnormal IMF (with respect to other interacting galaxies) could be explained if there are no massive molecular clouds. Indeed, Larson (1981) argued that in the Magellanic Clouds massive stars are formed only in massive molecular clouds. The formation of massive molecular clouds in NGC 7752 could be inhibited by the existence of a flow of diffuse material from NGC 7753 which could prevent their formation due to cloud-cloud collisions as expected for interacting galaxies (Norman and Silk 1980) and, therefore, the resulting physical and dynamical conditions could favor Schmidt's law–type star formation. Evidence for the existence of such a flow comes from the high extinction and the asymmetric Hα intensity distribution in NGC 7752.

VI. CONCLUSIONS

Star-formation properties for a sample of interacting galaxies are analyzed and the main results can be summarized as follows.

1. A high frequency of LINERs was detected among the sample galaxies. Many of these galaxies show only low-level activity and are not associated with high IR flux LINERs.
2. Their global star-formation rates are higher than for field galaxies, at least in one of the colliding galaxies, in most of the systems. When star-formation activity is detected in more than one of the components, it tends to be higher than for isolated galaxies in all of them.
3. The star-formation activity is mainly concentrated toward the central parts of the strongly interacting galaxies. Extended emission can appear in galaxies of every spectral type when the activity level is very high, but it is not a general feature.
4. The star formation in a galaxy in every generation of its "ecologic cycle" of molecular cloud and star formation is found to be essentially produced with the same spatial distribution.
5. Star formation is found to depend on the galaxy interactions being increased for a large fraction of the binary pairs for which the distance between the interacting components is less than seven projected main galaxy diameters.

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