HYPERACTIVE STAR BURSTS IN CLUMPY IRREGULAR GALAXIES

J.Heidmann
Observatoire de Paris
92195 Meudon
France

ABSTRACT. Clumpy irregular galaxies have been identified as giant irregulars with a clumpy structure. Investigations in the visible, UV, radio centimetric, X-ray and far infrared demonstrated that the clumps are hyperactive bursts of star formation, each equivalent to a hundred giant HII regions like 30 Doradus or NGC 604. In spite of their strong activity, their linear size is smaller than half a kpc, leading to an "olive jar" model with very peculiar physical conditions. These could be related to the non-detection of the 2.6-mm CO line and to our discovery in a clump of the first known case of a strong, compact, variable radio source which is not a galactic nucleus.

1. GENERAL IDENTIFICATION

Clumpy irregular galaxies were originally recognized from morphological criteria: 5-10 high surface brightness compact clumps loosely scattered all over the body of the galaxy (Casini and Heidmann 1976a, b) (Fig.1). Note that their morphology has no relation with the one of multi-nuclei galaxies.

They were discovered among UV-excess irregular galaxies as having, surprisingly, a wide 21-cm neutral hydrogen line, contrary to normal irregulars in which internal motions are moderate (Bottinelli et al. 1973, 1975, Casini et al. 1979).

Clumpy irregular galaxies are more luminous, more extended and more massive than classical irregulars (Table I). Optical spectra of the clumps show the typical HII region emissions lines, with electron temperatures 9 000 K, electron densities around a hundred per cubic cm and a slight deficiency in O and S. Supernova remnants are indicated by a high [SII]/Hα ratio (Boesgaard et al. 1982).

2. MASSIVE STARS AND IONIZED GAS

Crucial informations were obtained from International Ultraviolet Explorer UV spectra of the clumps. Very good fits can be made with mixtures of early type O8V main sequence plus B8Ia supergiant stars (Fig.

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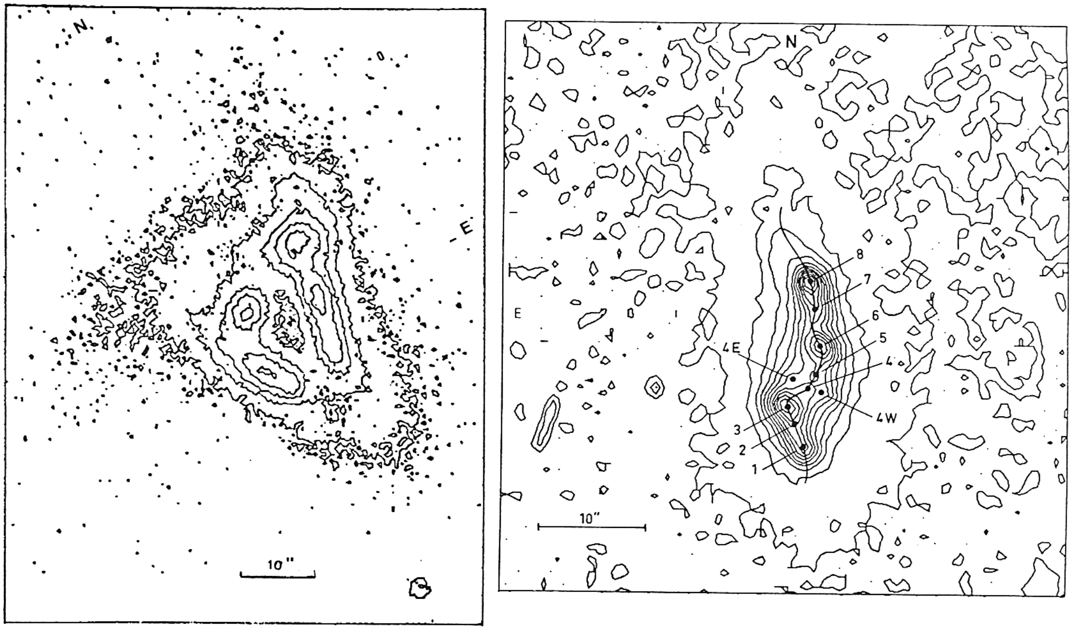

Figure 1. Isophotal maps of Mkr 8 and 296.

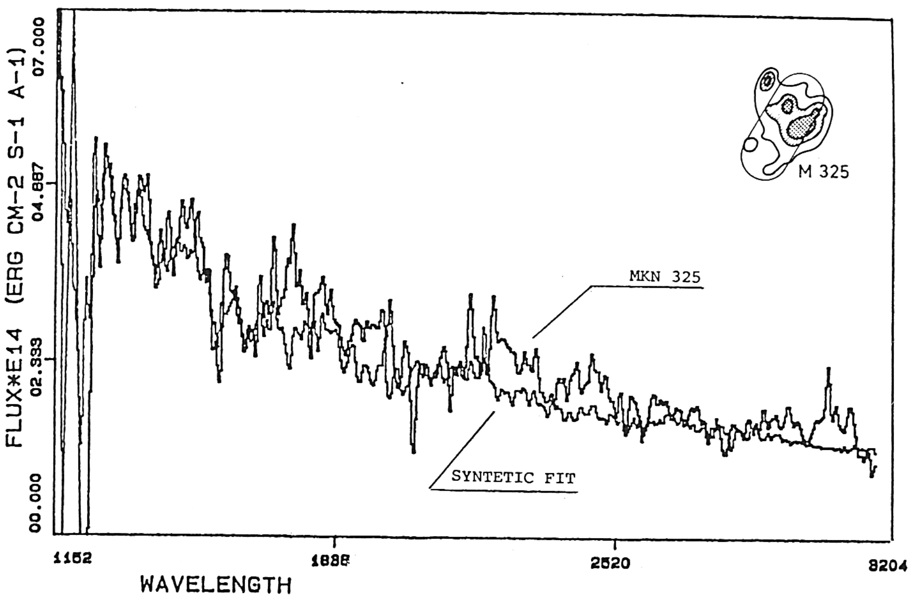

Figure 2. UV spectrum of Mkr 325 with a synthetic fit from a mixture of early stars; top right: slit position on the galaxy.

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2). The clump average luminosity in the far UV reaches 2 10**27 erg s**-1 Hz**-1; this means that one clump radiates on the average a hundred times as much as the 30 Doradus giant HII region and should have a correspondingly high level of star forming activity (Benvenuti et al. 1979, 1982a, b).

Such a high level of activity was confirmed by centimetric radio observations with the Effelsberg 100-m dish (Fig.3) and at the Very Large Array (Fig.4). The clumps, which are imbeded in a steep spectrum envelope, have flat spectra, suggesting thermal emission from an optically thin gas. The ionized gas mass is found to be 10**8 solar mass per clump and the corresponding Lyman continuum photon flux reaches 5 10**53 s**-1 (Heeschen et al. 1981, Heidmann et al. 1982, Yin et al. 1984). Note that these values are only lower limits because no correction is made for an unknown internal absorption in the clumps.

The envelope radio emission is probably synchrotron radiation from high energy electrons produced by supernova events. Indeed HEAO-2 Einstein observations of the clumpy galaxy Mrk 325 showed a very powerful X-ray emission: 2 10**41 erg s**-1 in the 0.5-4.5 kev band. This is a tremendous level, equivalent to 10 000 powerful SN remnants or to 1 000 X-ray binary stars like LMC X-1 (Heeschen and Heidmann 1983).

3. STAR FORMING ACTIVITY

The overall electromagnetic spectrum of Mrk 325 could then be obtained (Fig.5). A general comparison in the radio, near IR, visible, UV and X-ray bands with other major extragalactic HII complexes showed that an average clump has a star forming activity equivalent to 90 times the one of 30 Doradus, or 6 times more than a chain of giant HII regions such as NGC 5461 in the ScI galaxy Messier 101. Though the clumpy irregular galaxy Mrk 325 is not more than 10 times brighter than the Large Magellanic Cloud, it is three orders of magnitude more active in star formation (Heidmann 1983).

4. AN "OLIVE JAR" MODEL

Most surprisingly, high resolution imagery of this galaxy showed that the clumps have linear sizes not exceeding 500 pc (Fig.6). This means that though clumps have each a 100 times the star forming activity of 30 Doradus proper (the Tarantula Nebula), whose size is 100 pc, their size is not larger than the 500 pc overall dimension of the 30 Dor complex, as given for exemple by radio continuum maps (Coupinot et al. 1982).

This leads to an "olive jar" model in which a clump would be a tight package of 5x5x5, i.e. a hundred, 30 Dor proper cores, each 100 pc large, confined within a 500 pc volume (Fig.7). Such a stuffing of active regions should produce very peculiar physical conditions through high space-densities of energetic radiations, stellar winds, shock waves.

Such peculiar conditions may be related to our non-detection of the 2.6-mm CO line in clumpy irregular galaxies: relative to neutral hydrogen content, their CO emission is less than one tenth of the one of our

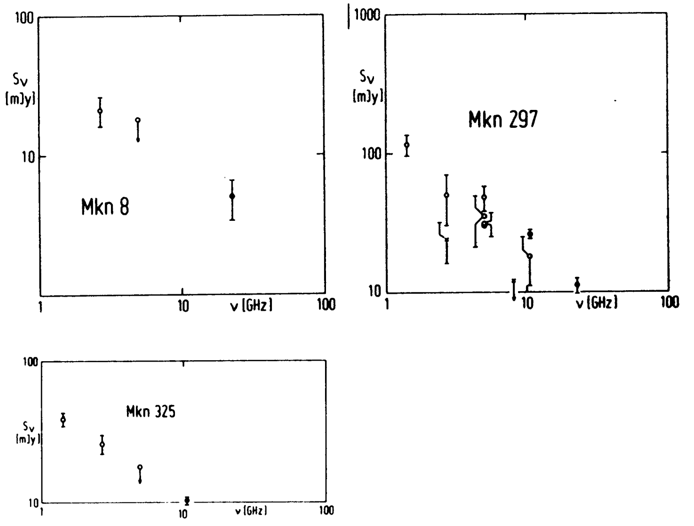

Figure 3. Global radio spectra of Mkr 8, 297 and 325.

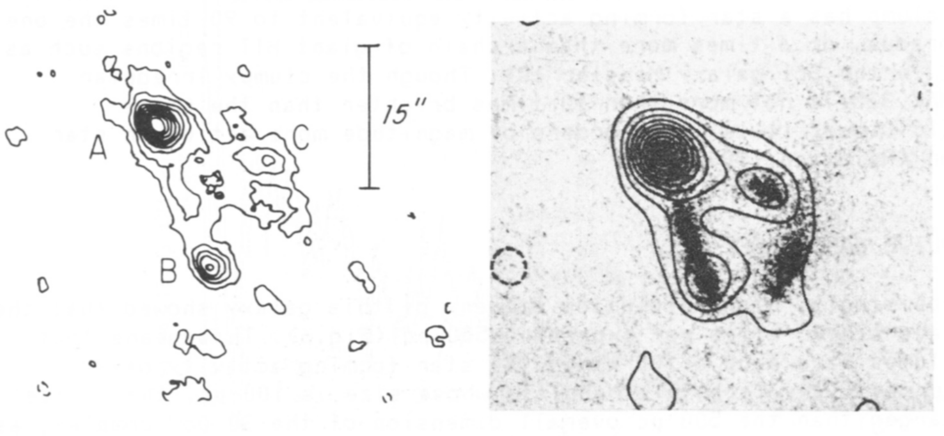

Figure 4. VLA maps of Mkr 8 at 6 and 20-cm wavelength.

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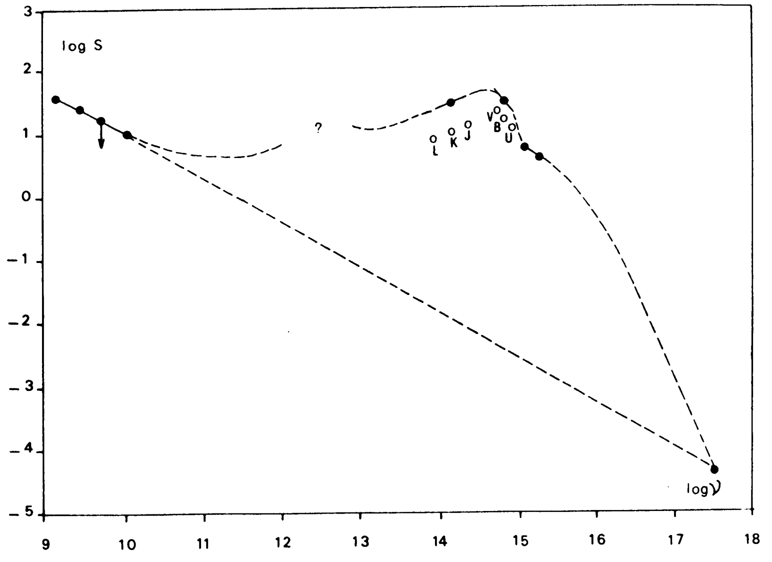

Figure 5. Overall spectrum of Mkr 325 in mJy vs. Hz.

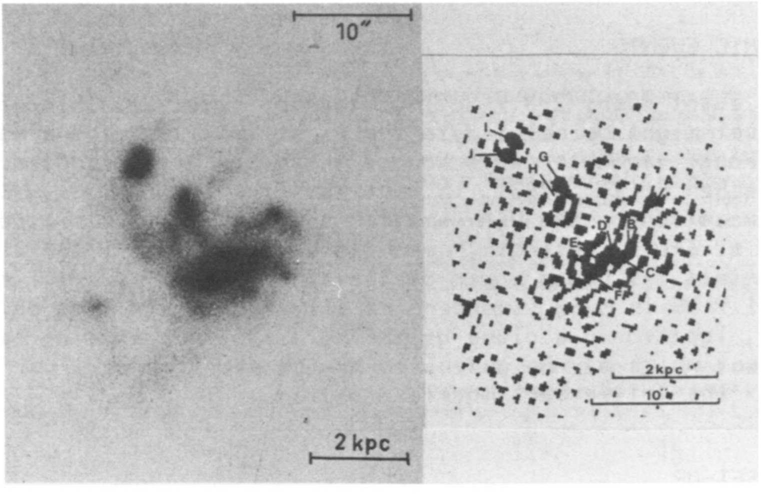

Figure 6. High-resolution photograph and high-contrast deconvolved isophotal map of Mkr 325.

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Galaxy; when compared to Messier 82 central star forming region our limits indicate that the clump star forming activity occurs in physical conditions more similar to those of M 82 than to those of our Galaxy (Gordon et al. 1982, Sofue et al. 1985).

5. FAR-INFRARED EMISSION

Though the hyperactive nature of the clumps is well documented, most wanted data were still lacking in the far IR. Fortunately clumpy galaxies have been detected by the InfraRed Astronomical Satellite (Klein et al. 1986). They show a very strong maximum in the 100-μm region, comparable in shape to those of giant HII regions like NGC 604 in M 33 or violently star forming galaxies like M 82 (Fig.8). This far IR emission is due to thermal radiation from dust heated by the bursting stars, with dust temperatures around 40 K.

The dip in the spectra in the millimetric range is compatible with previous estimates for the thermal radio emission to be about 20% of the one at 2.8 cm. This corresponds to a production rate of Lyman continuum photons reaching 6.7 10**54 per second for Mkr 297. Because of absorption by dust the real rate is still higher. The radio to FIR flux density ratios for Mrk 8 and 297 are significantly higher than for galaxies at large. This may be due to the large number of massive stars in these two clumpies, in agreement with the IUE results.

The FIR luminosities are very high; Mrk 297 emits over 10**44 erg s**-1, i.e. 3 times the FIR luminosity of M 82. This can be accounted for by 4 10**6 massive stars of 10 solar mass each. With an assumed lifetime 10**7 years, this yields an average star formation rate of 4 solar mass per year, 10 times more than for an average "IRAS minisurvey" galaxy.

6. CATACLYSMIC EVENTS

A supernova event every 2-3 years may then be expected. This high activity level might be related to the first known case of a non-nuclear, compact, strong, variable radio source which has been reported in a galaxy (Heeschen et al. 1983). In two year time this source, Mkr 297A (Fig.9), unresolved by the VLA (smaller than 100 pc), increased by a factor of 3 at 6-cm wavelength, reaching a radio power 6 10**21 W Hz**-1. This is 43 times the radio power of the already very powerful radio young supernova 41.9+58 in M 82 (Kronberg et al. 1985). This kind of "hypernova", located in a clump of Mkr 297, is a new type of cataclysmic powerful event which may be generated by the peculiar physical conditions suggested by the "olive jar" model.

7. SPATIAL SET-UP

Clumpy irregular galaxies are rare and far away objects, difficult to observe; we know only half a dozen of them and for their investigation we had to use instruments all over the world among the best and most

Figure 7. A model of the "olive jar" model. A clump is a jar of olives and each olive is a Tarantula Nebula.

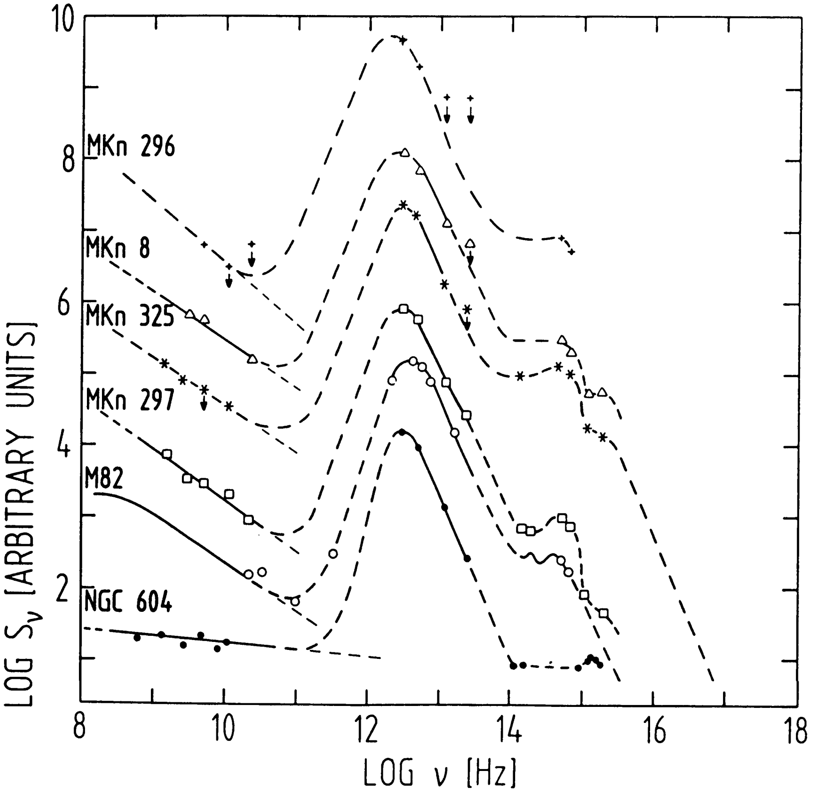

Figure 8. Overall spectrum of four clumpy irregular galaxies, Messsier 82 and NGC 604 in flux density (arbitrary) units vs. Hz.

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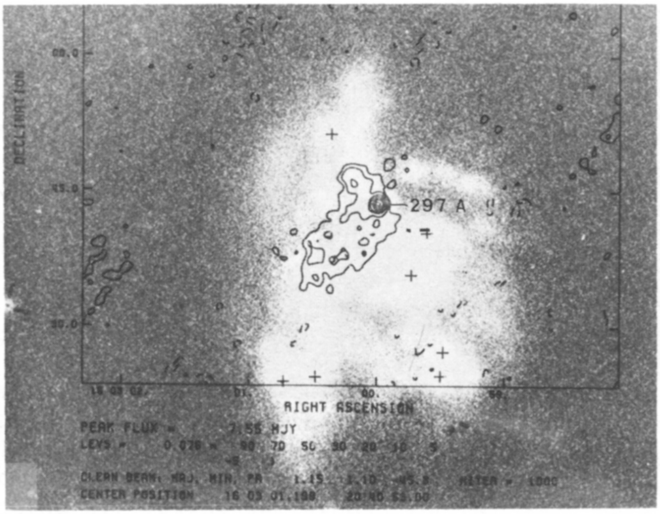

Figure 9. VLA map of Mkr 297 at 6-cm wavelength superimposed on its optical image.

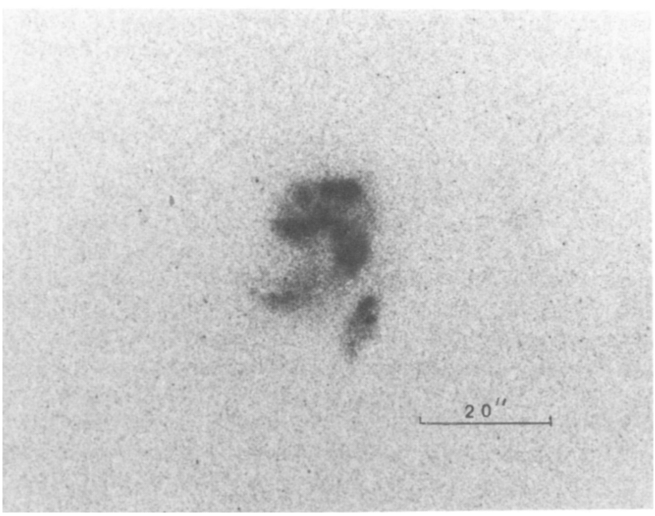

Figure 10. High-resolution photograph of KUG 1624+413, a new possible clumpy irregular galaxy.

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TABLE I: Condensed properties of clumpy irregular galaxies

galaxy		Mkr 7	Mkr 8	Mkr 296	Mkr 297	Mkr 325
other name		UGC3838	IC2184	A1601+19	NGC6052	NGC7673
distance (H = 75 Km/s.Mpc)	Mpc	43	50	63	63	49
number of bright clumps		5	5	8	10	10
U-B		-0.38	-0.40	-0.42	-0.37	-0.43
B-V		0.25	0.39	0.42	0.44	0.35
21-cm line width	km/s	310	330	195	415	250
absolute magnitude	pg	-19.7	-20.0	-18.9	-20.9	-21.1
photometric diameter	kpc	11	16	15	18	26
indicative total mass	10**9 sun mass	30	130	16	91	49
neutral hydrogen mass	10**9 sun mass	2.4	4.6	3.4	10	3.8
5th clump absolute magnitude	B				-13.0	-16.1
5007/4861 line intensity ratio		2.5	1.9	2.1		2.3
(6717+6731)/4861 line int. ratio		0.7	1.5	0.8		1.3
O/H abundance ratio	10**-4	3.5		3.5		
S/H abundance ratio	10**-6	2.8		3.5		
clump electron temperature	K	8 900	<12 700	8 700		<10 600
clump electron density	e/cc	<100		200		
155-nm luminosity (per clump)	10**27 erg/s.Hz	1.6	1.2		2.0	2.1
2.8-cm radio luminosity	10**28 erg/s.Hz		2.6		12.4	2.8
radio spectral index			-0.7		-0.8	-0.7
clump mean spectral radio index			-0.2			
ionized gas mass (per clump)	10**8 sun mass		1.4			
X-luminosity (0.5-4.5 Kev band)	10**41 erg/s					2.2
star forming activity	30 Doradus units					900
CO/HI mass ratio	10**-3	<0.5	<0.1	<0.6	<0.2	<0.3
2.2-μm IR luminosity	10**28 erg/s.Hz					8.6
dust temperature	K		38	35	40	42
6.3-cm/60-μm flux density ratio	10**-3		6	3	6.5	3.5
Lyman continuum photons	10**54 photon/s		>1.4		>6.7	>1.6
far IR luminosity	10**43 erg/s		3.8	1.8	16.4	7.2
target clump for HST/FOC		W	A	7	radio	C

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sophisticated ones. We searched for more such galaxies (Casini and Heidmann 1978, Barbieri et al. 1979). The most promising case is the UV-excess Kiso galaxy KUG 1626+413 (Fig.10), an irregular 20 kpc across, with absolute magnitude -21, containing ten blue clumps and having the same FIR luminosity as Mkr 297 (Maehara et al. 1987a).

At the start our searches have been biased towards paired Markarian galaxies; as a matter of fact two clumpies, Mkr 7 and 8, are in a pair and also Mrk 296 and 297 which furthermore are in the same galaxy group as the Seyfert "Sextet". In order to get a clearer view of the neighborhoods of clumpy galaxies we are using different selection criteria with the Kiso work (Maehara et al. 1987b).

The nearly simultaneous triggering of hyperactive clumps across all of the body of a galaxy is of course a major problem. In a deep photographic investigation we discovered a faint arc 22 kpc away from the clumpy galaxy Mkr 325 (Dettmar et al. 1984) which may be indicative of tidal interaction. However there does not seem to exist a unique explanation for our different cases.

8. CONCLUSION

The series of investigations reported here have lead to the identification of galaxies with a peculiar morphology which are producing very intense bursts of star formation, among the most intense known today. They raise important problems for the questions of formation and of evolution of galaxies as well as of stars; at the same time they bring new informations which might be relevant for these matters.

For further insight in the peculiar physics of the hyperactive clumps, we elaborated a proposal for the detailed investigation of a selection of them with the Faint Object Camera of the Hubble Space Telescope, the radio clump Mkr 297A being one of them (Heidmann et al. 1984).

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ZINNECKER: You drew attention to the first non-nuclear variable radio source (in Mrk 297) and the possibility of a cataclysmic event. The timescale for variability (∿ 2 years) would be consistent with a collision of two massive stars which I have shown can occur in the core of giant extragalactic H II regions (see IAU Symp. No. 116). The collision should be associated with considerable X-ray emission. Are there any observations of X-ray emission from this source?

HEIDMANN: Unfortunately not. Though we obtained 40 000 seconds of observing time with the *Einstein* satellite we could use only 4 000 because of the end of its carreer. Furthermore, clumpy galaxies are too far away fro the *Exosat* instruments.

MAEHARA: In the course of the Kiso survey, about 3 000 and 1 800 UV-excess galaxies have been detected and catalogued, respectively. It is shown from the follow-up observations of bright samples that this survey is a fainter extension of Markarian's one, that is, most of these galaxies are starburst galaxies of various types.

HEIDMANN: Yes, and I would like to add that in our last year work with Japanese colleagues on this KISO survey, we found a possible case of clumpy galaxy out of three KUG's only. So it looks as a very good survey.

SOFUE: Could you compare the IR, Radio, and Optical luminosities of CIG's with those of normal galaxies *like the Milky Way or M31?*

HEIDMANN: The IR luminosities of CIG's reach 3 times the M82 one. For the radio centimetric power they reach up to 10 times the M82 level. So a CIG can be looked at as a collection of clumps, each of them being typified by the M82 inner few hundred parsec star forming region. As for the optical comparisons with spiral galaxies it can be said for example that though the ScI M101 galaxy and the CIG Mkn 325 have comparable optical levels, the latter has a star forming activity 15 times larger.