EVIDENCE FOR ENHANCED STAR FORMATION IN IRAS-DETECTED MARKARIAN GALAXIES

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Abstract. The IR emission of 640 Markarian galaxies (MrkG), included in the IRAS Survey, is considered as an evidence for enhanced star formation rate (SFR) in these objects. About 73% of the MrkG have high far-infrared luminosities (ca. 10E + 44 erg s^{-1}) in 1–500 mcm IR spectral band. The distribution of $\log(f_{60}/f_{100})$, peaked at about 45 K, shows that IRAS MrkGs have a tendency to extend the relation f_{60}/f_{100} vs L_{ir}/L_{bi} for 'normal' S glaxies. They emit up to hundred times more IR energy in 40–120 mcm band than in optics. The mean ratio log $\langle L_{ir}/L_b \rangle$ for 621 IRAS MrkG with known redshifts is 2.2.

It is suggested that there are two IR emitting components in the IRAS MrkG – a warm one connected with the UV-fluxes of the newborn massive stars, re-radiated by dust, and a cool one, originated from the dust in galactic disks and heated by the general interstellar radiation field. The warm IR luminosities and warm IR fractions are determined on the basis of IR colour–colour diagrams α(25/12), α(60/25), and α(100/60). The mean warm IR fraction for all Mrk IRAS detected galaxies with well-defined IR fluxes is 0.83 when the grain mass absorption coefficient model with $n = 0.0$ is used. The dust mass responsible for the IR flux at 60 mcm is derived to be about 10E + 5 $M_\odot$, assuming the dust clouds are optically thin, and using the dust temperature $T_d \sim 46$ K (deduced from the $f(60)/f(100)$ ratio). There is a relation between L_{ir} and L_{bl} which points out that the most IRAS MrkG have rather enhanced SFR.

1. Introduction

Surveys widely carried out in the last decades at optics have produced large sets of emission-line galaxies (ELGs). In the majority of the observed galaxies with emission lines in their spectra the line emission probably is an indicator of gas photoionized by hot, young stars associated with the regions of active star formation. On the other hand, most of the energy emitted by such stars at short optical wavelengths actually is detected by us as re-radiated by dust far-infrared (FIR) emission. That is why, as have been noted by Salzer and MacAlpine (1988), the investigation of the FIR properties of samples of optically selected ELGs is important for gaining a better knowledge of the energetics of these galaxies, as well as for understanding the galaxy activity, both Sy-like and induced by star-formation processes. The use of the database accumulated by infrared Astronomical Satellite (IRAS) provides the best opportunity to select subsets of ELGs with well-manifested FIR properties. One of the optical surveys carried out is the list of Markarian galaxies (MrkG) (Markarian *et al.*, 1989). This set contains 1500 galaxies with ultraviolet excess. The present paper considers the infrared radiation of a sample of 638 MrkG included in *Catalogued Galaxies and Quasars Observed in the IRAS Survey* (Lonsdale *et al.*, 1985) which contains about 43% of the whole Markarian's list. Six-hundred twenty-one of IRAS-detected MrkG have known redshifts, and 102 of them have well-determined IRAS fluxes.

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2. General Properties

If we use IRAS data we ought to do a comparative studying of the parameters of the star formation in the different type Markarian galaxies. As a first step we have choosed the two components model of de Jong *et al.* (1984).

The basic data are presented in Table I. The mean and its variance are presented for 50 Sy1, 35 Sy2, 8 Sy3, 84 SBG, 426 normal Markarian galaxies with measured radial velocities and IRAS fluxes and for 102 objects with well-defined fluxes as well. The last rows belong to the Markarian galaxies as a group. The data in the column are as follows: type of activity, redshift, blue luminosity in (ergs s^{-1}), infrared luminosity in (ergs s^{-1}), infrared excess. $F(12)$–$F(25)$ ratio, $F(25)$–$F(60)$ ratio, $F(60)$–$F(100)$ ratio, dust temperature (F_{12}/F_{25}), dust temperature (F_{60}/F_{100}), spectral index (100/60), spectral index (60/25), spectral index (25/12), and dust masses using $F(60)$. The activity types are as by Veron–Cetty and Veron (1989).

We assume that the infrared radiation of the galaxies in question is due to dust thermal re-radiation of the stellar radiation field.

As indicators of the 'infrared activity' of galaxies the IR luminosities L_{ir} and the ratio L_{ir}/L_{bl} may be used, where L_{bl} is taken to be equal of $\nu f(\nu)$ at $\lambda = 4400$ Å. We have used the calibration of Houck *et al.* (1984) in the blue region f:

$$\log f(B) = -7.54 - 0.4\,\mathrm{mp}\,, \quad (1)$$

where $f(B)$ is expressed in (W m^{-2}) and mp is the apparent photographic magnitude from the *Catalogue of Galaxies and Clusters of Galaxies* (CGCG – Zwicky *et al.*, 1961–1968). Note that these fluxes are about 5 times larger than those in standard B-filter (Soifer *et al.*, 1987).

2.1. Infrared Luminosities and Colours

Infrared fluxes f refer to the infrared emission between 40 and 120 mcm which is determined according to Dennefeld *et al.* (1985) as

$$f(\mathrm{IR}) = 1.75(2.55f_{60} + 1.01f_{100}) \times 10\mathrm{E}-14 \quad \mathrm{W\,m^{-2}}\,, \quad (2)$$

where f_{60} and f_{100} are the IRAS cataloged flux densities in Jy. We have used Equation (2) in order to compare our results with those of other authors for different kinds of objects.

If we follow Belfort *et al.* (1987), we have estimated the total far infrared emission F_{fir} from about 1 to 500 mcm by the expression

$$f(\mathrm{FIR}) = 1.75(12.66f_{12} + 5.0f_{25} + 2.55f_{60} + 1.01f_{100}) \times 10\mathrm{E}-14\,. \quad (3)$$

The distribution of the total FIR luminosities L_{fir} for a sample of IRAS-detected MrkG with known redshifts (consisting of 621 objects) is shown in Figure 1. All the luminosities. L(Bl), L(IR), and L(FIR), have been computed assuming a pure Hubble flow with $H = 75$ km s^{-1} Mpc^{-1} and $q = 1.0$. It should be noted that about 73% of all IRAS-detected MrkG have $L_{fir} > 10\mathrm{E}+44$ erg s^{-1}. In fact, this means that these

TABLE I

Median and average values for some basic parameters of the Markarian galaxies

MrkG		z	$\mathrm{Log}\,L_{bl}$	$\mathrm{Log}\,L_{ir}$	$\mathrm{Log}\,R$	R_1	R_2	R_3	Td_1	Td_2	Al_1	Al_2	Al_3	Md60
Sy1	m	0.0338	43.84	44.10	0.23	−0.24	−0.18	−0.33	238.0	45.8	−1.10	−0.85	−0.60	5.40
50	×	0.0376	43.82	44.06	0.25	−0.23	−0.20	−0.34	238.7	48.0	−1.04	−0.89	−0.63	5.40
	σ	0.021	0.45	0.40	0.46	0.15	0.16	0.23	32.8	9.2	0.66	0.61	0.52	0.48
Sy2	m	0.0257	43.67	44.16	0.50	−0.15	−0.30	−0.45	215.4	51.2	−0.70	−1.20	−0.90	5.30
35	×	0.0296	43.65	44.17	0.52	−0.17	−0.30	−0.52	226.0	51.8	−0.76	−1.36	−0.93	5.40
	σ	0.015	0.55	0.58	0.44	0.16	0.26	0.28	54.2	9.9	0.73	0.74	0.81	0.60
Sy_3	m	0.0351	43.87	44.30	0.34	−0.28	−0.10	−0.69	255.8	44.0	−1.30	−1.85	−0.30	5.70
8	×	0.0353	43.82	44.22	0.40	−0.26	−0.16	−0.64	247.6	45.4	−1.20	−1.70	−0.50	5.60
	σ	0.015	0.28	0.47	0.34	0.12	0.19	0.20	37.9	6.2	0.54	0.51	0.58	0.38
SBG	m	0.0144	43.38	43.60	0.26	−0.21	−0.26	−0.69	220.8	47.6	−0.95	−1.80	−0.85	5.00
84	×	0.0163	43.25	43.55	0.30	−0.21	−0.27	−0.64	227.9	48.4	−0.96	−1.68	−0.84	4.80
	σ	0.012	0.61	0.69	0.39	0.12	0.21	0.22	38.5	6.9	0.55	0.58	0.67	0.74
Norm	m	0.0210	43.38	43.72	0.31	−0.28	−0.08	−0.48	261.6	44.0	−1.30	−1.30	−0.20	5.20
426	×	0.0236	43.31	43.63	0.32	−0.29	−0.13	−0.48	255.5	44.5	−1.30	−1.27	−0.40	5.10
	σ	0.014	0.52	0.63	0.39	0.16	0.17	0.26	38.1	6.3	0.70	0.69	0.52	0.69
Well	m	0.0168	43.54	44.00	0.45	−0.17	−0.35	−0.72	207.6	49.6	−0.80	−1.90	−1.10	5.30
102	×	0.0216	43.51	43.99	0.48	−0.18	−0.34	−0.62	219.3	50.3	−0.84	−1.64	−1.05	5.20
	σ	0.015	0.53	0.61	0.49	0.20	0.24	0.32	61.9	9.1	0.91	0.84	0.74	0.70
All	m	0.0210	43.45	43.79	0.30	−0.27	−0.11	−0.50	254.7	44.7	−1.20	−1.30	−0.30	5.20
617	×	0.0244	43.37	43.70	0.33	−0.26	−0.16	−0.50	248.0	45.9	−1.19	−1.31	−0.51	5.10
	σ	0.016	0.56	0.65	0.40	0.16	0.19	0.26	40.4	7.3	0.70	0.70	0.60	0.69

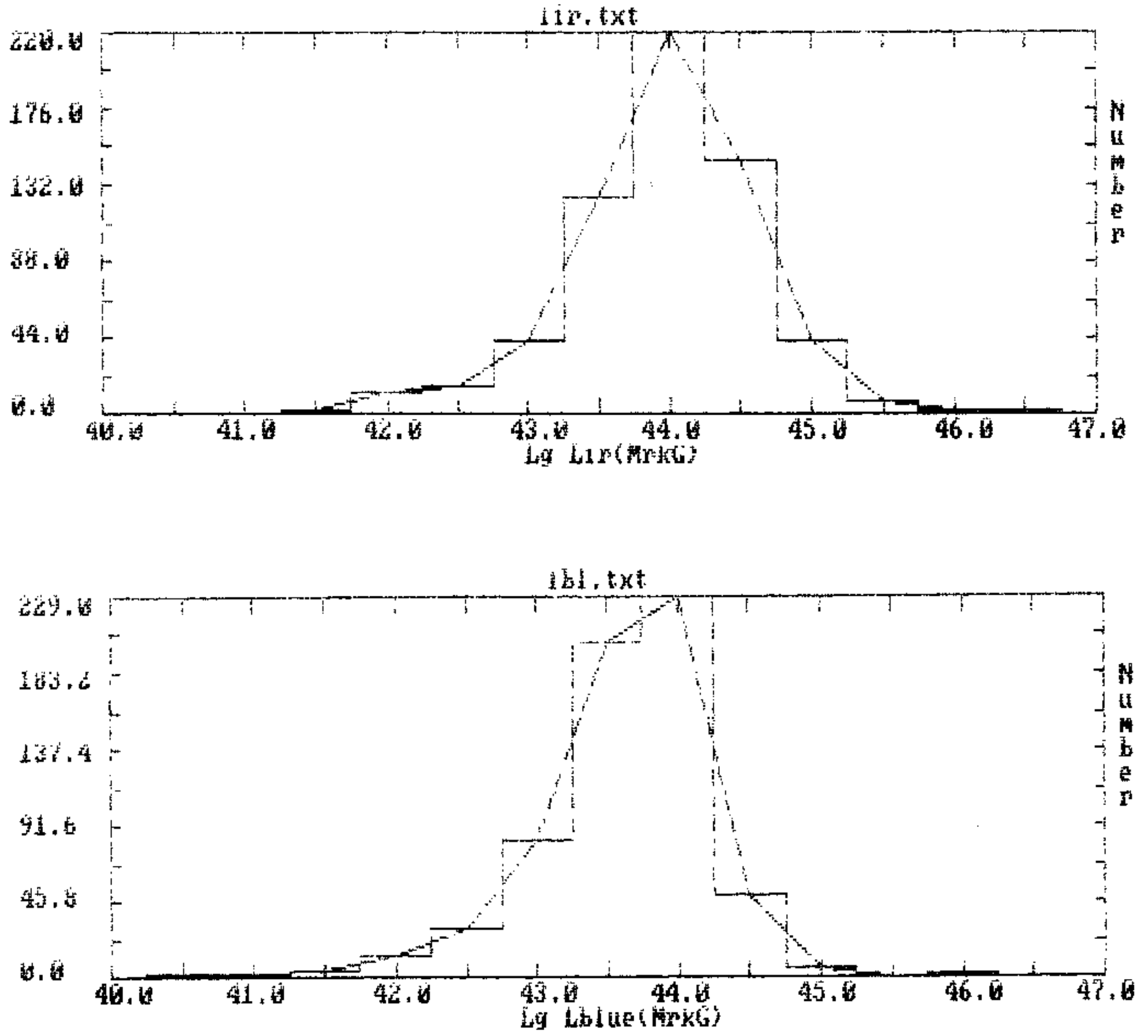

Fig. 1. Distribution of the FIR and blue luminosity of all 621 MrkG with known redshifts found in the *IRAS Point Source Catalogue*.

MrkG belong to ELIRS (extremely luminous far-infrared sources – see Harvit *et al.*, 1987). because they have both strong IR radiation within 1–500 mcm band and low-ionized optical spectra.

Figure 2 shows the distribution of the colour index ratios f_{60}/f_{100} for our sample of five different samples of IRAS-detected Markarian galaxies (from lower to upper panel – 'normal' MrkG, Markarian Starburst galaxies; Sy3, Sy2, and Sy1, Mrk galaxies). The mean infrared colour for the sample of 621 IRAS-detected MrkG with known redshifts is $\langle \log(f_{60}/f_{100}) \rangle = -0.26$ and the mean ratio $\langle L_{ir}/L_b \rangle = 2.2$. The corresponding values for the 'normal' S galaxies are $\langle \log f_{60}/f_{100} \rangle = -0.43$ and $\langle L_{ir}/L_b \rangle = 0.4$ (see de Jong *et al.*, 1984). It may be seen that the IRAS-detected MrkG are warmer than the 'normal' S galaxies, with distribution peaking clearly at $T \sim 45$ K. It can be seen also that the IRAS MrkG have a distribution of temperature colour index f_{60}/f_{100} similar to that of the BCELGs (Kunth and Sevre, 1985).

The infrared colours f_{100}/f_{60} vs the indexes of activity L_{ir}/L_b for the sample of 621 IRAS-detected MrkG with known redshifts are plotted on Figure 3. On this diagram 102 objects with well determined IRAS fluxes at 60 and 100 mcm are marked. The region occupied by the 'normal' S galaxies picked out from the Virgo cluster is outlined by a solid line. On the same figure the BCELGs would have occupied the upper right part. Thus, IRAS-selected MrkG extend the same relation for the normal S galaxies (see Kunth and Sevre, 1985).

The ratio f_{60}/f_{100} has been adopted by many authors as a convenient measure of the infrared activity of galaxies. In Figure 3 there is a tendency of increasing of the dust temperature derived from f_{60}/f_{100} and the galaxies become warmer with the IR activity (L_{ir}/L_b ratio). This has been already mentioned by de Jong *et al.* (1984) for the 'normal' S members of the Virgo cluster. IRAS-detected MrkG tend to extend this relation and the BCELGs show the same tendency. At temperatures 40–50 K IRAS-detected MrkG emit up to hundred times more energy in the infrared than in the optical blue band. It should be noted that the region occupied by IRAS-selected MrkG coincides with the one occupied by IRAS-selected MrkG coincides with the one occupied by the BCELGs. This result probably points at higher star formation rate (SFR) in these galaxies than in normal spirals and irregular galaxies.

2.2. Dust masses

The IR emission of the dust is caused mainly by the dust component with low temperature (about 30 K for the cirrus emission). In the optically thin case the mass of the dust emitting at a given wavelength is determined as

$$M_{\text{dust}}(l) = 4\pi r^2 f_\lambda / 4\pi B_\lambda(T_d)\,K\,, \tag{4}$$

where r is the distance to the galaxy; f_λ, the observed flux density at wavelength λ; T_d, the dust temperature; $K = Q/(4/3)a\rho\ \text{cm}^2\ \text{g}^{-1}$, the mass absorption coefficient; and $Q \sim \lambda^{-n}$ is the absorption efficiency of the dust. We assume that the dust is a mixture of graphite and silicate particles with density $\rho = 2\ \text{g cm}^{-3}$, whose radii a are equal to 0.1 and 1.0 mcm. We adopt $n = 1$ and the corresponding mass absorption coefficients are based on the recent grain models by Draine and Lee (1984).

The dust masses generating the observed IR-flux at 60 mcm have been obtained using Equation (4), where the dust temperatures T_d were deduced only from f_{60}/f_{100} ratio if $n = 1$ grain absorption model is adopted. By this way we found that the mean dust of IRAS-detected MrkG is $M_d\,(60\ \mu\text{m}) \sim 10\text{E}+5\ M_\odot$. A correlation might be expected between the ratio L_{ir}/L_b which characterizes the starburst activity and the dust mass radiating at 60 and 100 mcm. Such a correlation for 621 IRAS-selected MrkG with known redshifts, if only the graphite grains of 0.1 mm are taken into account, is shown in Figure 4. As far as the dust masses were defined using the $F(60)$ mcm we have to expect some relation between the two parameters. This is in accordance with the evaluation of the masses of the dust clouds in the Galaxy. Very interesting is the fact that a large part of Markarian galaxies being elliptical and SO objects and a lack of deficit of interstellar matter. By use of the two components model as a standard we have

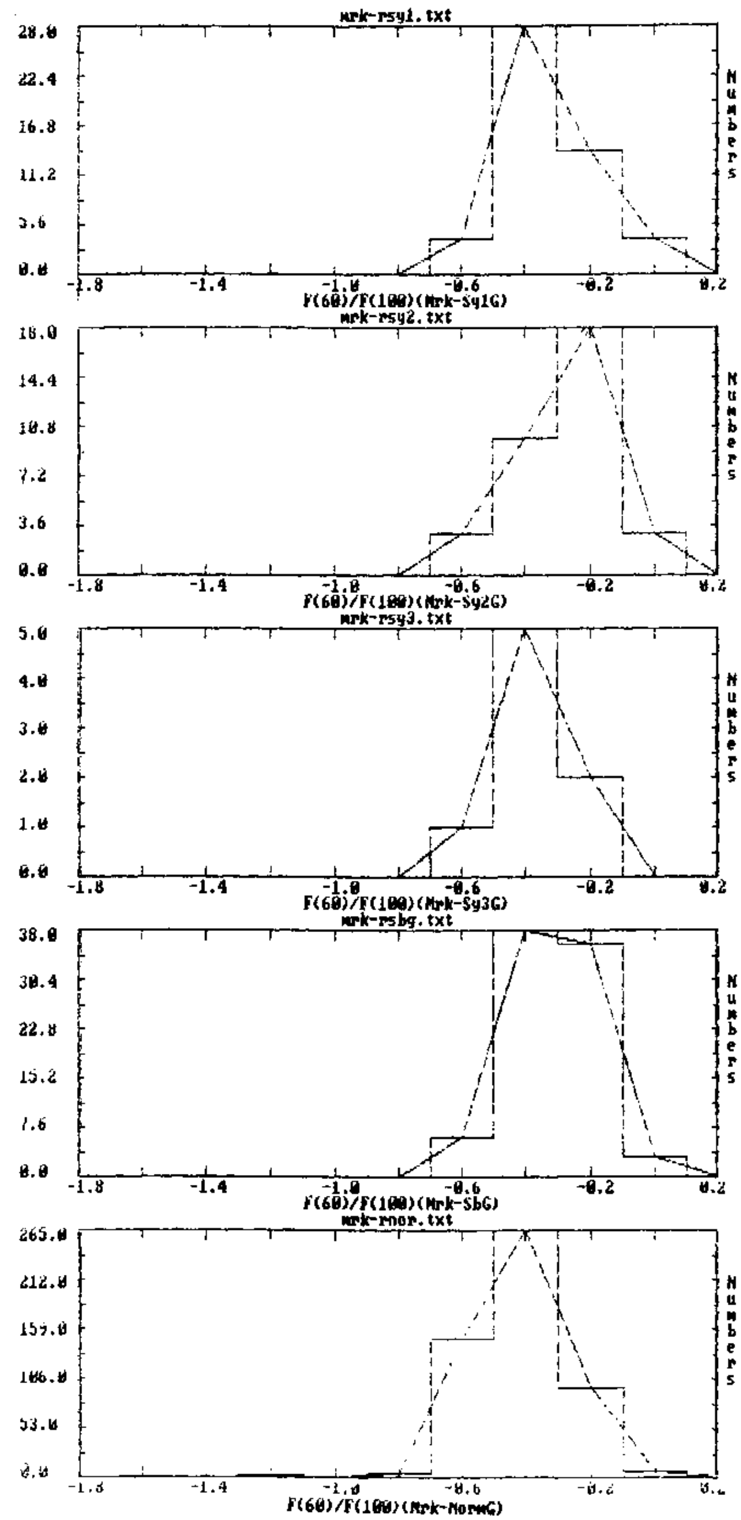

Fig. 2. Distributions of the $f(60)/f(100)$ ratio of five different samples of IRAS-detected Markarian galaxies (from lower to upper panel – 'normal' MrkG, Markarian Starburst galaxies; Sy3, Sy2, and Sy1, Mrk galaxies).

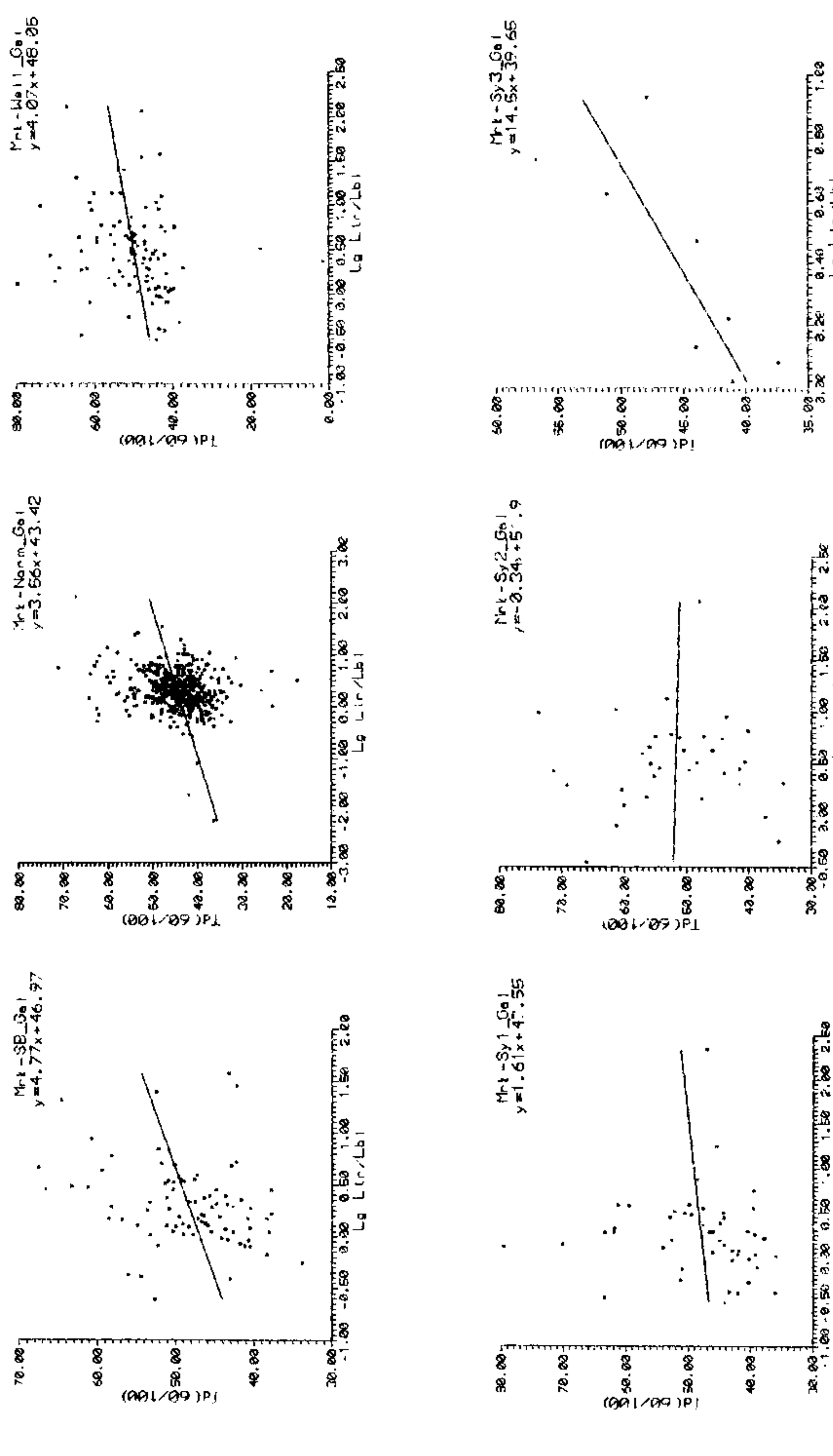

Fig. 3. Relation between the dust temperature $T_d(60/100)$ vs the index of IR activity L_{ir}/L_b for all 621 IRAS MrkG with known redshifts. One-hundred and two objects with well-determined IRAS fluxes are also presented.

possibility to make only qualitative description of the different groups of Markarian galaxies. The general conclusion is the temperature of the dust is quite high – 40–50 K. The normal Markarian galaxies demonstrate very similar parameters – the infrared excess between 0 and 1 (only 10% have larger blue luminosities – i.e., infrared excess <0!). It is remarkable the Sy1 G demonstrate a lowest activity but as we mentioned above there are additional sources to heat the dust. The great dispersion in the dust temperatures for SB, Sy1, and Sy2 Markarian galaxies probably is real. The group with well-measured fluxes (a mixture of all type objects!) has quite a high dust temperatures and big dispersion too from 40 to 80 K.

2.3. Star formation rates

The star formation rate is considered from a point of view of the relation between L(IR) and L(Bl) (see Gallagher and Hunter, 1987). This relation for above mentioned 621 MrkG is presented in Figure 5. On the same picture the lines of constant (middle line), declined (lower line), and increased (upper line) SFR are presented. Most of them lie between the lines of constant SFR and starburst. Some of them are obviously above the latter. This indicates an increased SFR in the IRAS-detected Markarian galaxies. If we follow Gallagher and Hunter (1987), we can made a raw estimation of SFR

$$dM/dt = 2.5 \times 10E - 10\beta^{-1}\delta L(\mathrm{FIR}) \quad M_{\odot}\,\mathrm{year}^{-1}\,, \tag{5}$$

if the mass of the warm stars is near to 10 $M_{\odot}$. Here $\beta \sim 0.5$ and it depends both on the newborn star effective temperature and on galaxy's geometry. The part δ of the infrared radiation, which is connected with the young stars, must be < 1.0, and according to our estimation it is about 0.55 ($n = 1$ dust grain absorption model adopted). As a result it was obtained $dM/dt \sim 8\ M_{\odot}\,\mathrm{year}^{-1}$.

The picture is too different for the different types of Markarian galaxies – probably this is reflection of the presence of additional heater of the dust. There is practically strictly correspondence between the luminosities in the blue and far infrared for the normal Markarian galaxies. That means practically all the ultraviolet radiation from the young stars is converted into infrared emission by the surrounded dust. Similar is the picture for the Star burst – and H II – Markarian galaxies, but there are few high luminosity objects, using the Crawford's criteria. Probably these are objects with increasing Star Formation Rate.

Seyfert 1 Markarian galaxies do not confirm the picture above – there is very weak relation between L_{fir} and L_{blue}. The same is the situation with Seyfert 2 Markarian galaxies but the blue luminosities are ca. an order lower.

3. Results

The mean colour temperature for the total sample of 638 IRAS-selected MrkG based on the f_{60}/f_{100} ratios is about 46 K and it differs from 250 K, the temperature based on the f_{12}/f_{25} ratios (all values are determined within the $n = 1$ dust grain absorption model). So we may expect that the IR radiation generated by dust re-radiation of the

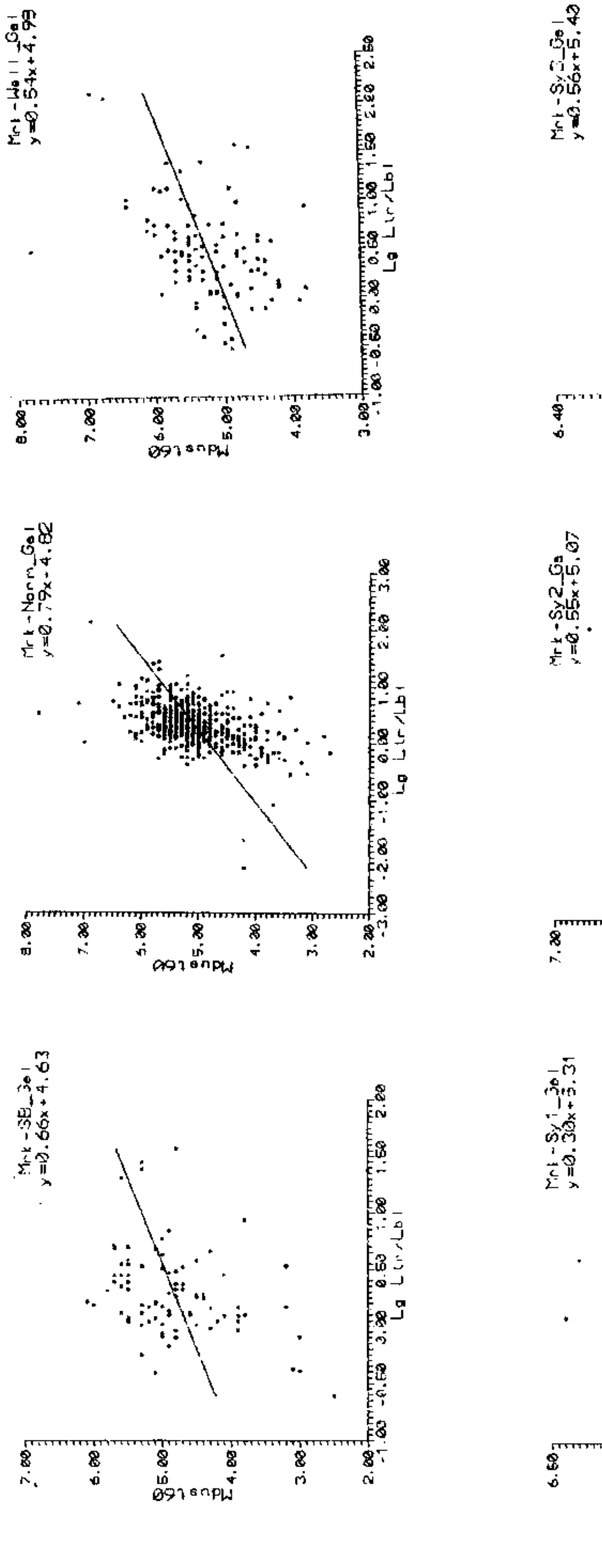

Fig. 4. Correlation between the dust mass radiating at 60 mcm (at Td deduced only from f_{60}/f_{100} ratio and $n = 1$ model) in solar mass units vs the L_{ir}/L_b ratio.

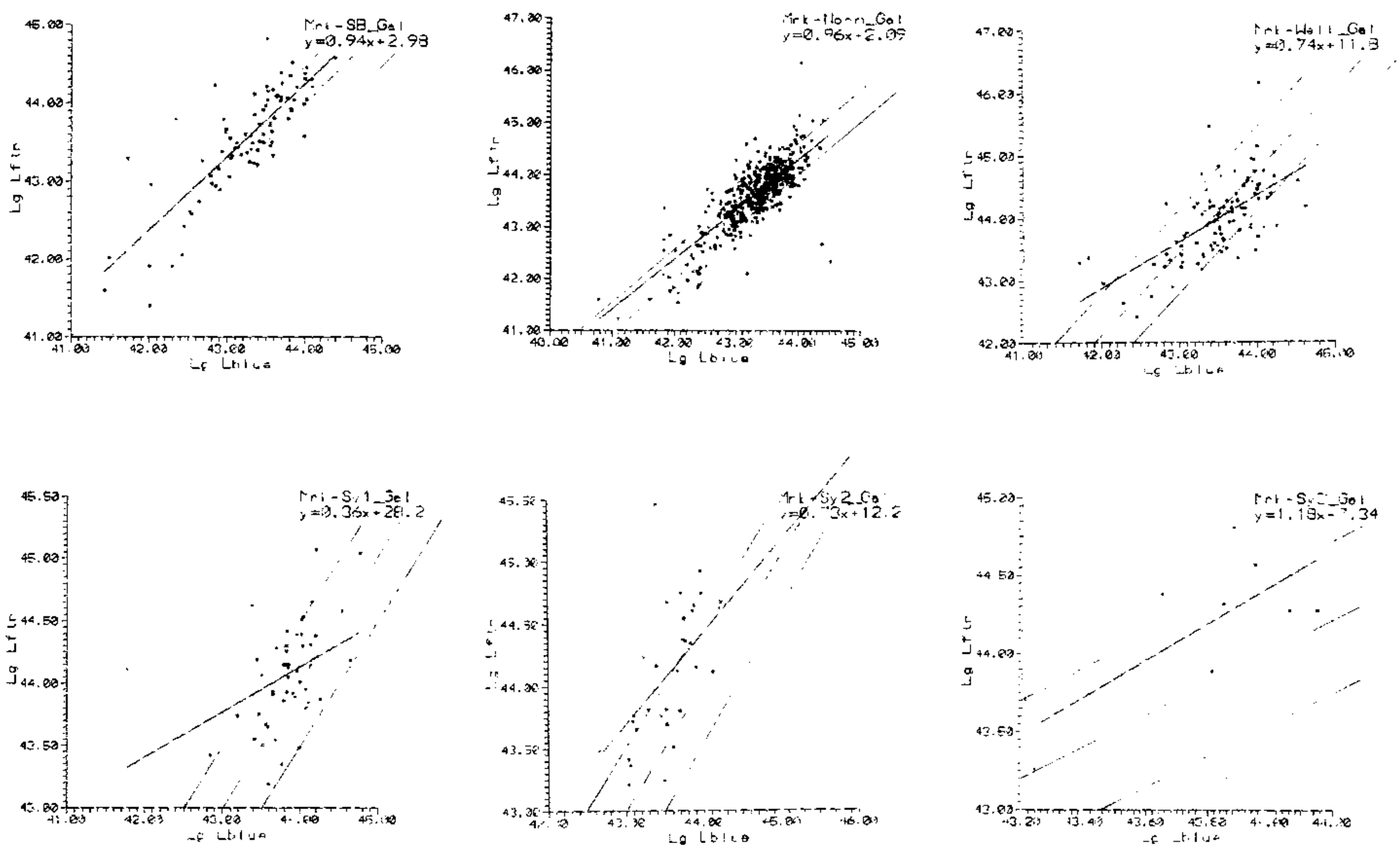

Fig. 5. The IR luminosity L(IR) between 40 and 120 mcm vs the blue luminosity L(Bl). The lines of constant SFR (in the middle), the starburst (upper) line and the line of declining (lower) SFR are superimposed according to Gallagher and Hunter (1987).

UV photons of newborn massive stars originates in two differently situated dust clouds. If we follow Hunter *et al.* (1987), and for convencience only, we could refer to them as the 'near-dust' and 'far-dust' IR components.

'Near-dust' IR component is connected with the radiation at 12 and 25 mcm coming from hot dust located in (or at least very near) the H II regions situated around the newborn massive stars. The mean dust colour temperatures, derived from the ratio f_{12}/f_{25}, concern these regions.

'Far-dust' IR component is related mainly to the radiation at 60 mcm and less to that at 100 mcm. This radiation arises in a warm dust associated with a neutral gas outside of the ionized gas region or in the associated neutral molecular gas clouds, out of which the H II regions have formed. The mean colour temperatures, derived from the ratio f_{60}/f_{100}, concern the dust, which is essentially responsible for the 'far-gust' IR component.

There is a third IR component which is cooler than the 'far-dust' one. It originates from the dust in galactic disks heated by the general interstellar radiation. Thus, it resembles the 'cirrus' radiation in our Galaxy. As in the Milky Way, we consider the dust temperature of this IR component to be about 30 K.

As it was noted above, only 102 IRAS-selected MrkG have well determined IRAS fluxes. We include them in a separate subset sample. Their IR emissions have been assumed to be proportional to $v^n B_v(T)$, where $B_v(T)$ is a Planck function. Two-black-body model spectrum has been adopted for the emission at 60 and 100 mcm. They are the 'cirrus' black-body radiation at 30 K, and the black-body emission of the warmer 'far-dust' component, which temperature is 50–120 K (Sekiguchi, 1987).

If we use measured fluxes in 12, 25, 60, and 100 mkm we had defined the spectral indexes for each object. In Figure 6 we had plotted the line $\alpha(100/60) = \alpha(60/25)$ corresponded to the power law of the radiation. One could to mark on for every group of objects there are galaxies above the line $\alpha_1 = \alpha_2$ – i.e., disposed in the region traditionally occupied by the quasars. A half of normal Markarian galaxies also in fact are lower limits. Nevertheless obviously there is enhanced star formation in all type of Markarian galaxies. By use of Sekiguchi's (1987) analysis of similar relation $CI(100/60)$–$CI(60/25)$ one could to determine the temperature of the dust, the part of the IR emission at 60 mkm and some qualitative evaluations for each object. Only 5 objects from total 621 dispose below the black-body line.

4. Discussion

The members of the subset have been plotted on the two-colour diagram. $\log(f_{60}/f_{100})$ against $\log(f_{12}/f_{25})$, which is presented on Figure 7. This relation practically presents the Helou's (1986) model. The two lines on the picture corresponds to the Helou model. Above the short line is the region occupied by the objects with higher star formation rate. The cross point and below is the region where typically the cirruses lay. Only four objects with well-defined fluxes dispose in that region and Mrk 1022 is worthy to be remembered.

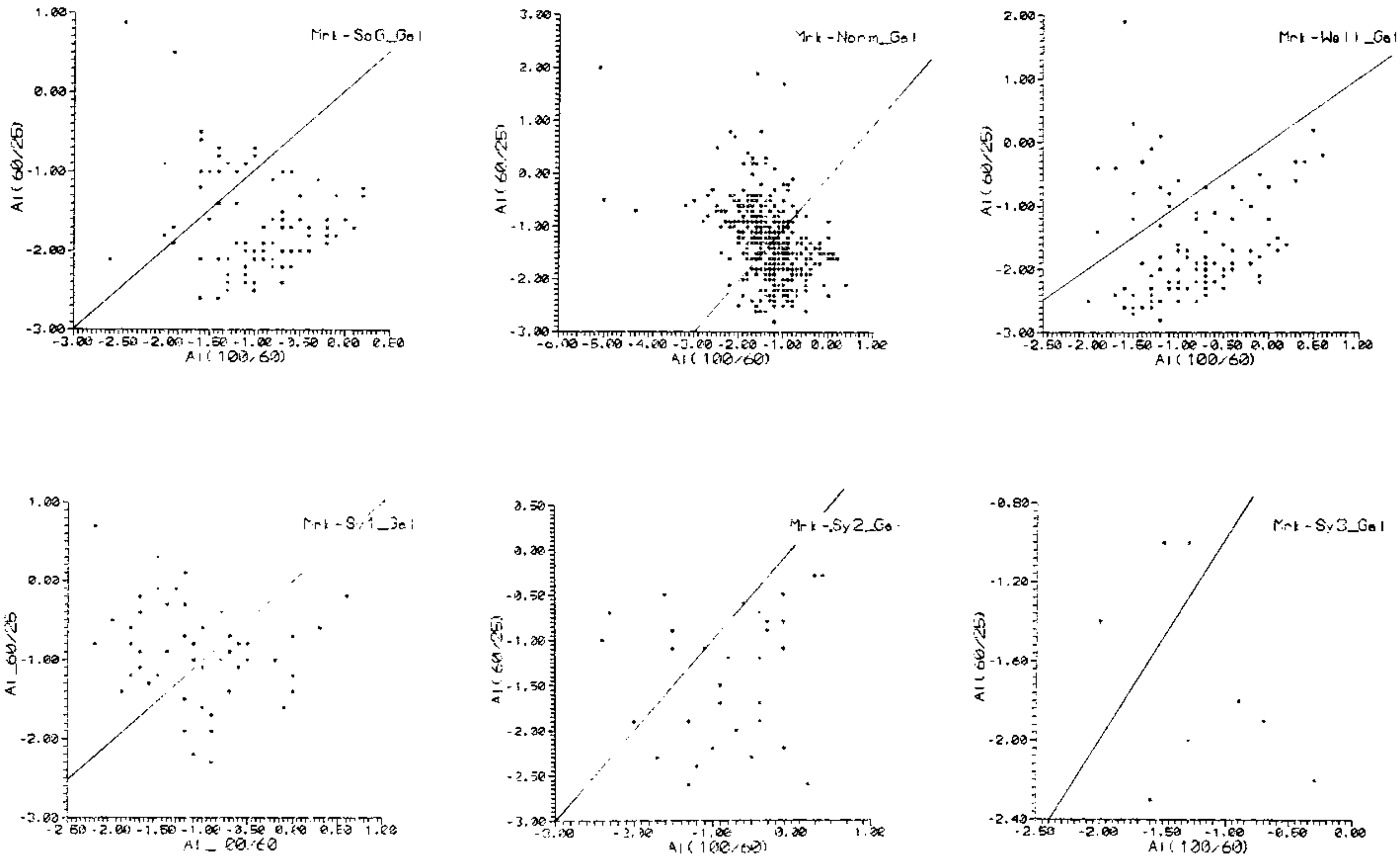

Fig. 6. IR colour–colour diagram Al(60/25) against Al(100/60) for 102 IRAS-detected MrkG sampled in our subset. The right-hand line (where the temperature is marked) is formed only by the warm IR component. Along the two-temperature model curve the warm fractions at 60 mcm for (60) are given.

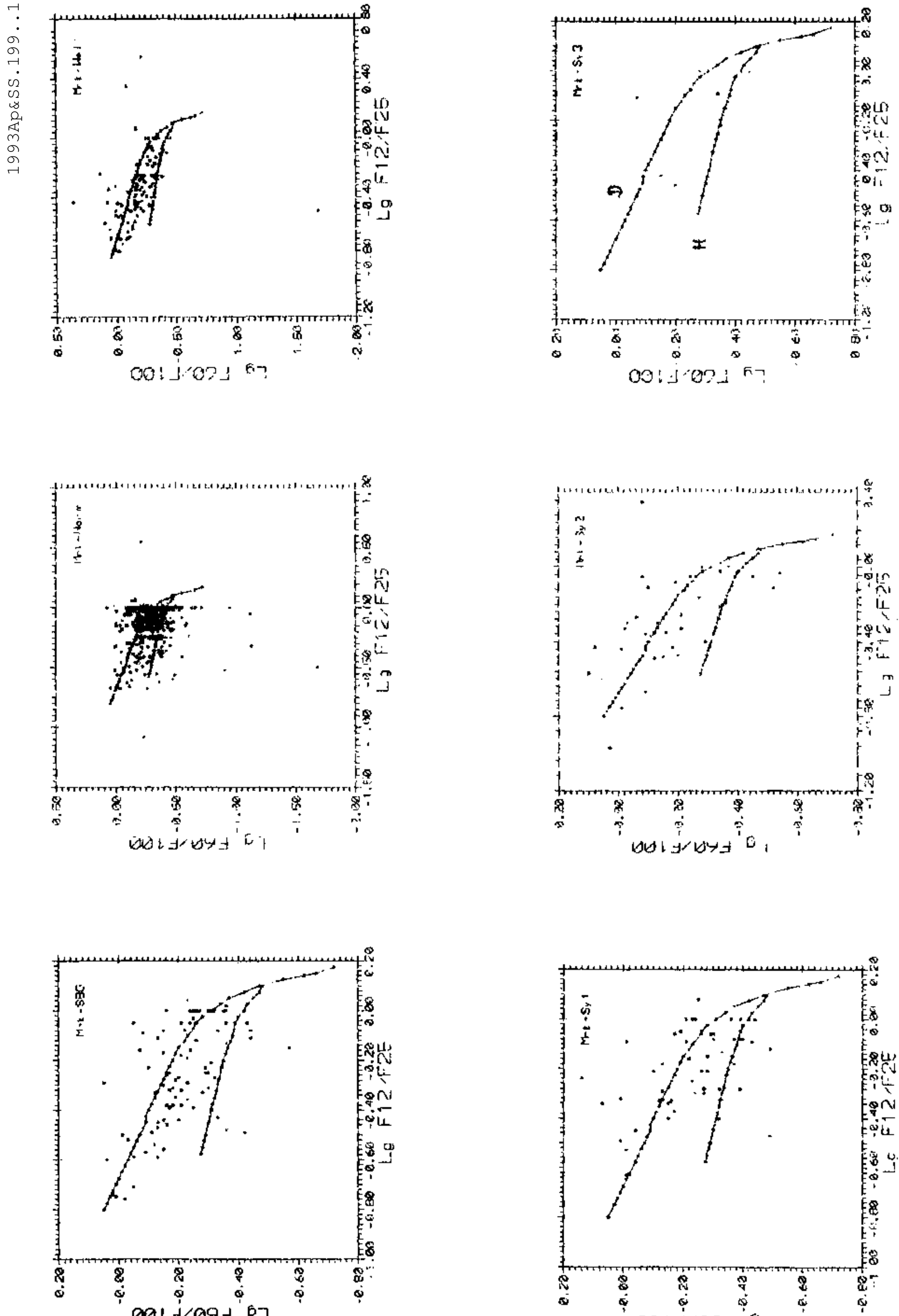

Fig. 7. IR colour–colour diagram $\log(f_{12}/f_{25})$ against $\log(f_{60}/f_{100})$. Helou's (1986) model is superimposed there.

With exception of the galaxies with Seyfert-like nuclei, the far-IR radiation is a result of thermal re-radiation from interstellar dust grains heated by starlight. The FIR model, proposed by Helou (1986), consists of two components – a cirrus-like one and a warm one, connected with active star forming regions. To trace curve D in his paper, Helou (1986) used an estimation made by Desert (1986) of the emission from dust particles of various sizes and convenient heating radiation field. The last one was altered from an intensity comparable to the solar neighbourhood (point X), to one similar to the intensity found in the regions of active star formation (point Y). The other curve H was computed from Helou's (1986) two-component model and it represents the locus of points in the colour-colour diagram, where the contributions from the warm and cool components are equal.

Most of the galaxies on this diagram, where the ratio L_{ir}/L_b increases from the lower right to the upper left corner, are placed between curves D and H. This indicates that the IRAS-detected MrkG are objects with enhanced star-formation rate.

The objects lying definitely above the line D on the Helou diagram have been considered as the most interesting ones in the subset.

5. Conclusions

On the basis of the discussion above the following conclusions have been made:

(1) About 73% of IRAS-detected MrkG show high total IR luminosities $L_{\rm fir} \gg 10{\rm E}+44$ erg s^{-1} in 1–500 mcm IR spectral region.

(2) The distribution of $\log(f_{60}/f_{100})$ shows that the IRAS MrkG are warmer than the 'normal' S galaxies with clear peak at about $T = 45$ K ($n = 0$ model). The temperature colour index f_{60}/f_{100} of IRAS MrkG is distributed similarly to that of the BCELGs.

(3) IRAS-selected MrkG tend to extend the relation f_{60}/f_{100} vs L_{ir}/L_{bl} for 'normal' S galaxies and emit up to hundred times more energy in the IR spectral band between 40 and 120 mcm. Its mean ratio $\langle L_{ir}/L_{bl} \rangle$ of IR luminosities to blue ones is about 2.2.

(4) It is very likely that in IRAS-detected MrgG there are two IR components – warm one, connected with the UV fluxes of newborn massive stars, re-radiated by dust, and cool one, originated from dust in galactic disks, which is heated by the general interstellar radiation field. The ability to deduce total warm IR luminosities $L_{\rm fir}$ and warm IR fractions $L_{\rm fir}/L_{\rm fir}$ rests on IR colour–colour diagrams $\alpha(25/12)$, $\alpha(60/25)$, and $\alpha(100/60)$. The mean warm IR fraction is $\langle L_{\rm fir}/L_{\rm fir} \rangle \sim 0.83$, if the grain mass absorption coefficient is $n = 0.0$.

(5) If the dust clouds are optically thin, the dust mass of IRAS-detected MrkG, which is responsible for IR flux densities observed at 60 mcm, is derived to be $M_d(60\ {\rm mkm}) \sim 10{\rm E}+5\ M_\odot$.

(6) There is a correlation between L_{ir} and L_{bl}, which indicates that the most IRAS-detected MrkG have enhanced rather than constant star formation rate.

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