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A new approach to the radio – far infrared correlation for non-calorimeter galaxies

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Abstract. New radio continuum data for a sample of 74 spiral galaxies supports the calorimeter model of Völk (1989) only for steep-spectrum, thin-disk, non-interacting objects which comprise $\simeq$ 30% of the sample. As the spectral indices correlate neither with far infrared surface brightness nor with average (equipartition) magnetic field strength, the data disagree with the model for non-calorimeter galaxies of Helou & Bicay (1993).

We are able to explain the radio – far infrared correlation for non-calorimeter galaxies, globally and also on kiloparsec scales within galaxies, with the help of two basic relations with the *average volume density of the gas* as the primary factor. Firstly, there is strong evidence that the strength of the equipartition magnetic field is correlated with the volume density ρ of the (almost) neutral gas, following a power law with an exponent of $m = 0.48 \pm 0.05$ for the galactic averages of our sample. Secondly, taking the thermal radio emissivity as an indicator of the average star-formation rate (SFR), we obtain a 'Schmidt law' (SFR $\propto \rho^{n}$) with n = 1.4 ± 0.3. The FIR luminosity is linearly related to SFR. Finally, we assume equipartition between the energy densities of the magnetic field and of the cosmic rays which relates the synchrotron emissivity to the field strength. Combination of these relations leads to a radio – far infrared luminosity correlation with a power-law exponent of x = 1.3 ± 0.3, very close to what is observed (x = 1.25 ± 0.08). Forthcoming ISO satellite data can be used as a test of our approach.

Key words: galaxies: spiral – galaxies: ISM – infrared: galaxies – radio continuum: galaxies – ISM: cosmic rays – ISM: magnetic fields

1. Introduction

The tight and universal correlation between the far infared (FIR) and radio continuum emission of galaxies is one of the most important results of the IRAS mission because a connection between thermal and non-thermal processes in the interstellar medium is not at all obvious. The correlation was first detected by de Jong et al. (1985) for a large sample of spiral galaxies at a radio wavelength of λ6.3 cm and by Dickey & Salpeter (1984) in galaxies of the Hercules Cluster. In the following years the importance of the correlation became more and more obvious. It holds over more than four orders of magnitude in luminosity and is valid for all kinds of star-forming galaxies, e.g. normal Sbc spirals (Hummel et al. 1988), spirals and irregulars (Wunderlich et al. 1987, Wunderlich & Klein 1988), Blue Compact Dwarf Galaxies (Klein & Wunderlich 1987, Klein et al. 1991), and for group and cluster galaxies (Menon 1991, Helou et al. 1985). The correlation does not just reflect a 'richness effect' (Xu et al. 1994a), but can be attributed to a coupling between the dust-heating photons, emitted by young, massive stars, and the synchrotron-emitting relativistic electrons of the cosmic rays. Hence, the correlation is valid for the emission of the star-forming disk. This is further supported by the fact that the correlation also holds on kiloparsec scales within galaxies (Beck & Golla 1988, Bicay et al. 1989, Bicay & Helou 1990, Fitt et al. 1992, Xu et al. 1992).

For galaxies containing an active nucleus the correlation does not hold. Sopp & Alexander (1991) showed that the radio emission of radio galaxies and radio-loud quasars is enhanced by two orders of magnitude compared to normal galaxies.

The correlation cannot be due to processes related solely to star formation, as too many steps are needed which involve too many parameters (see illustration by Ekers (1991)). The first theoretical approach to the correlation was the so-called calorimeter model of Völk (1989), who assumed that the relativistic electrons are completely trapped in their host galaxies and that the galaxies are optically thick for the dust-heating stellar UV photons. The FIR emission of the galaxies is assumed to be proportional to the supernova rate. This is supported by the results of Xu (1990) who found that the heating of FIR emitting dust is mainly due to UV radiation of high-mass stars (the supernova progenitors) for which galaxy disks are generally opaque. The same stellar population is thought to be responsible for the production of cosmic ray electrons. Additionally, a proportionality between the energy densities of the magnetic field and the

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interstellar radiation field is required. A more general approach by Lisenfeld et al. (1996) allows finite escape probabilities for the cosmic-ray electrons and final optical depth for the stellar UV radiation. Pohl (1994) developed a more general approach to this problem, including all kinds of energy losses of the cosmic rays.

Helou & Bicay (1993) argued that the correlation should also hold for optically thin galaxies and high escape probabilities for the electrons. This requires that the efficiency of extracting synchrotron emission from the cosmic ray electrons and the absorption of the dust-heating UV photons are proportional to each other. The coupling between the two mechanisms is produced by a relation between the magnetic field and the density of the interstellar gas. As in the calorimeter model, Helou & Bicay (1993) cannot explain the radio – FIR correlation on kiloparsec scales within galaxies.

Another model to explain the correlation via cosmic-ray driven chemistry in molecular clouds (Bettens et al. 1993) ignored the strong influence of the strength of the interstellar magnetic field on synchrotron luminosity and hence has to be regarded as inadequate.

The correlation is clearly non-linear which opened another field of discussion. Fitt et al. (1988) derived an exponent of x = 1.16 for radio flux densities at 151 MHz. They assumed that the FIR emission can be decomposed in a warm component related to the formation of massive stars and a cold, 'cirrus' component. Each component is characterized by a colour temperature defined by the ratio of the FIR fluxes at 60 μm and 100 μm. The cold component should be produced by low-mass stars and should not contribute to radio emission. Devereux & Eales (1989) found x = 1.28 for radio luminosities at 1.49 GHz and also tried to linearize the correlation, but claimed that the relative contribution of the two FIR components is dependent on the FIR luminosity.

An another attempt to explain the non-linearity Chi & Wolfendale (1990) proposed that the increasing escape probability of the cosmic-ray electrons from less luminous galaxies leads to a faster decrease in synchrotron luminosity than in FIR luminosity. This deficiency in synchrotron emission could also produce the decrease of the radio-to-FIR ratio for the most quiescent galaxies, as detected by Condon et al. (1991, herafter CAH91). According to these authors the decrease of the radio-to-FIR ratio with star-formation activity is also responsible for the non-linearity of the correlation.

Xu et al. (1994a) showed that the non-linearity of the correlation could be the result of different dependences of radio and FIR emission on the star-formation rate. Price & Duric (1992) showed for a small sample of galaxies that the thermal radio emission is directly proportional to the FIR emission and that the non-linearity may be produced by the synchrotron component. This result was confirmed for a sample of more than 70 galaxies observed at 10.55 GHz by Niklas (1996) (see below) who found a linear correlation between the thermal radio luminosity and that of the FIR, and a non-linear one between the synchrotron component and the FIR luminosity ($P_{\rm sync} \propto L_{\rm FIR}^{1.25\pm0.08}$).

A sample of Shapley-Ames galaxies brighter than $B_T = 12$ and north of $\delta = -25°$ was observed at λ2.8 cm (10.55 GHz) by Niklas et al. (1995a), using the 100-m radio telescope of the MPIfR Bonn. A detailed investigation of the radio – FIR correlation in the high-frequency regime based on this data set will be described in a separate paper (Niklas 1996). Here we use this survey to test the existing models of the radio – FIR correlation (Sects. 2 and 3) and take a new approach to explain the correlation in the case of non-loss-dominated radio spectra (Sect. 4).

2. Test of the calorimeter model

2.1. The spectral index of the total emission

A critical test of the calorimeter model proposed by Völk (1989) is the mean value of the non-thermal spectral indices of galaxies. In the calorimeter model it is assumed that the galaxies are 'optically thick' for relativistic electrons, i.e. that the electrons completely lose their energy due to synchrotron and/or inverse Compton losses in their host galaxy. In this case of complete trapping of the electrons one expects a synchrotron spectral index $\alpha_{\rm nth} \geq 1.0$ (where $S_{\rm nth} \propto \nu^{-\alpha_{\rm nth}}$) for injection spectra with $\alpha_{\rm o} \geq 0.5$. According to Biermann & Strom (1993) the energy spectrum of the relativistic particles in a shocked, adiabatic gas should be $\propto E^{-2.4}$ leading to an injection radio spectral index of $\alpha_{\rm o} = 0.7$.Diffusive shock acceleration in supernova remnants predicts $\alpha_{\rm o} \simeq 0.6$ (Bogdan & Völk 1983) yielding $\alpha_{\rm nth} \simeq 1.1$. However, this is not observed (Niklas et al. 1996a): The distribution of non-thermal spectral indices peaks sharply at $\langle\alpha_{\rm nth}\rangle = 0.85$ with a standard deviation of $\sigma_{\alpha_{\rm nth}} = 0.13$. The errors in $\alpha_{\rm nth}$ for individual galaxies are in the range of 0.05...0.15. Only some galaxies of the sample have spectral indices in agreement with the conditions of the calorimeter.

The model by Lisenfeld et al. (1996) allows finite escape probabilities for the relativistic electrons. In case of pure diffusive electron transport, and assuming a strong decrease of the magnetic field with increasing distance from the plane, Lisenfeld et al. (1996) predict non-thermal spectral indices between 100 MHz and 10 GHz in the range of $\alpha_{\rm nth} \simeq 0.9...1.0$. According to Niklas et al. (1996b) this is valid for only one third of the investigated sample. The other two thirds exhibit flatter spectra.

For a small sample of Blue Compact Dwarf Galaxies (BCDG's), Klein et al. (1991) found non-thermal spectral indices in agreement with the requirements of the calorimeter model and a very high fraction of thermal radio emission. Their radio-to-FIR ratio is in the range of normal spiral galaxies. Minimum energy calculations support the view that the relativistic electrons produced in the present starburst have lost their energy in a strong magnetic field. Additionally, due to the strong interstellar radiation field in these BCDG's, inverse Compton losses may also be important. On the other hand, Klein et al. (1991) found indications that in low-mass galaxies cosmic-ray confinement is less efficient. Hence, it is not clear whether BCDG's really act as calorimeters or if their position in the radio – FIR correlation can be attributed to their strong thermal radio emission.

2.2. Star-formation activity and electron transport

The activity of a galaxy can be described using the star-formation efficiency SFE, which is the ratio between its FIR luminosity and the mass of molecular hydrogen (Young et al. 1989). This quantity indicates how efficient a galaxy transforms molecular gas into stars. Young et al. (1989) presented the SFE for a large sample of galaxies. For 33 galaxies of the sample by Young et al., non-thermal spectral indices were determined (Niklas et al. 1996b). About 50% of the galaxies with relatively low SFE ($\simeq 2...4\,L_\odot/M_\odot$) have steep spectra. Examples for these quiescent galaxies with steep synchrotron spectra are: NGC 3521 ($\alpha_{\rm nth} = 1.12 \pm 0.09^1$), NGC 4501 ($\alpha_{\rm nth} = 1.19 \pm 0.04$) and NGC 7331 ($\alpha_{\rm nth} = 1.04 \pm 0.10$). On the other hand, very active galaxies (SFE $\geq 10\,L_\odot/M_\odot$) have flat non-thermal spectra: e.g. NGC 3310 ($\alpha_{\rm nth} = 0.61 \pm 0.04$), NGC 3504 ($\alpha_{\rm nth} = 0.70 \pm 0.04$), and NGC 4490 ($\alpha_{\rm nth} = 0.76 \pm 0.05$).

In these active galaxies convective outflow by a wind or the occurence of galactic fountains are expected. A connection between high star-formation activity and indications for a galactic wind has been pointed out by Lerche & Schlickeiser (1982). The influence of convective electron transport may flatten the synchrotron spectrum significantly. If adiabatic cooling losses are dominant, the low-energy electrons have similar spectra in disks and halos (Lerche & Schlickeiser 1982, Pohl & Schlickeiser 1990a). For high-energy electrons synchrotron and inverse Compton losses become important and hence their spectrum is steepened. Quantitative calculations of convective halo models require knowledge about the spatial distribution of the magnetic fields and the velocity field of the wind. Convection increases the escape probability of the cosmic-ray electrons, and the calorimeter conditions are not valid anymore.

However, there are also indications that the non-thermal spectral index is not exclusively coupled to the recent star-formation activity. NGC 2146 is an example of this opposite behaviour. It has a high SFE, but a very steep synchrotron spectrum ($\alpha_{\rm nth} = 1.11 \pm 0.06$). In NGC 2146, the large equipartition magnetic field strength of $\simeq 23\ \mu$G (Fitt & Alexander 1993, using k = 100 (see below)) causes strong synchrotron losses which may steepen the radio spectrum effectively.

If star formation varies strongly with time, aging of cosmic-ray electrons after a star-forming burst may also lead to steep spectra. However, in contrary to the lobes of radio galaxies where aging of the cosmic-ray electrons causes a spectral break at frequencies $\nu \simeq 1 - 10\,$GHz (e.g. Carilli et al. 1991), the cosmic-ray electron population should be refreshed continuously in star-forming galaxies. The time scale on which electrons are injected into the interstellar medium is determined by the lifetime of the supernovae progenitors ($\simeq 10^6$y) whereas the synchrotron age of cosmic-ray electrons in a magnetic field of 10μG causing a spectral break at 1 GHz is $\simeq 3 \cdot 10^7$ y. Hence, synchrotron aging can not affect the slope of non-thermal spectra in star-forming galaxies.

2.3. Thickness of the radio disks

The validity of the calorimeter conditions can best be tested for edge-on galaxies. Efficient confinement of the electrons in the galactic disk due to strong energy losses means absence of large radio halos. If the star-forming activity is low, so that no strong winds or fountains occur, the convective escape probability of the relativistic electrons is also low. A prominent example is the edge-on galaxy NGC 4565 with its thin radio disk. Magnetic fields mainly oriented parallel to the plane additionally suppress convective outflows. From high-frequency radio polarization observations of a sample of edge-on galaxies by Dumke et al. (1995) the orientations of the regular magnetic fields are known. Galaxies with thin disks and a magnetic field orientation parallel to the galactic plane tend to have steep spectra (e.g. NGC 4565: $\alpha_{\rm nth} = 1.18 \pm 0.11$; NGC 7331: $\alpha_{\rm nth} = 1.04 \pm 0.10$).

On the other hand, in galaxies with a large radio halo and a magnetic field which is perpendicular to the plane, e.g. NGC 4631, the synchrotron spectral index is significantly flatter ($\alpha_{\rm nth} = 0.78 \pm 0.04$). The radio halo galaxy NGC 4631 shows signs of strong star formation and interaction with its neighbours. Especially its Hα emission exhibits strong disturbances (Golla 1993). This indicates that in very active galaxies the escape probability of the cosmic ray particles is higher than assumed in the calorimeter model. NGC 4631 is believed to have a strong convective outflow (Pohl & Schlickeiser 1990b, Golla & Hummel 1994).

NGC 891 and NGC 253 (almost edge-on) with their extended radio halos (Hummel et al. 1991, Beck et al. 1994) are also clearly in disagreement with the calorimeter model ($\alpha_{\rm nth} = 0.78 \pm 0.03$ and 0.77 ± 0.05, respectively). The detection of bright X-ray halos (Bregman & Pildis 1994, Pietsch 1994) indicates gas outflows, in spite of the fact that the observed regular magnetic fields are mostly parallel to the plane.

2.4. Spectral steepening

The variation of the non-thermal spectral index with wavelength is another property of calorimeter galaxies. Strong synchrotron and inverse Compton losses lead to a steepening of the electron spectrum with increasing frequency at a break frequency (see e.g. Pohl 1993). Due to the broad frequency profile of the synchrotron spectral emissivity, this turnover is smooth even in case of an abrupt change in electron energy. As the magnetic field is not constant in a galaxy, the break frequency varies with position in the galaxy, so that the break frequency in the spectrum of the integrated synchrotron emission is further smoothed over some range in frequency. The modified calorimeter model predicts a steepening of $\Delta\alpha \simeq 0.06$ between 100 MHz and 10 GHz (Lisenfeld et al. 1996). The generalization of the calorimeter model by Pohl et al. (1991) takes into account all kinds

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[1] The errors in $\alpha_{\rm nth}$ were calculated for a fixed thermal fraction of the total emission at 1 GHz (Niklas et al. 1996b).

of energy losses, and the synchrotron spectra reveal stronger spectral steepenings ($\Delta\alpha \simeq 0.15...0.25$ between 100 MHz and 10 GHz) than those given by Lisenfeld et al. (1996).

The results of the separation of thermal and non-thermal radio spectra of 74 galaxies by Niklas et al. (1996b) indicate that the non-thermal spectra of most of the galaxies can be best described by a straight line with a typical error in the slope of $\simeq 0.03...0.07$, and that they do *not* steepen in the high-frequency range. This is confirmed by an independent estimate of the non-thermal spectral indices obtained by subtracting from the total radio emission the thermal emission which was computed using the Hα-line emission of the galaxies (Niklas et al. 1996b). Spectral steepening is observed only for a few galaxies in the sample of Niklas et al. (1996b). This indicates that synchrotron and inverse Compton energy losses are not important in the investigated frequency range of this sample.

On the other hand, interacting and cluster galaxies often show spectral steepening. The best studied example is NGC 2276 (Hummel & Beck 1995), member of a group of galaxies. Here the synchrotron spectral index increases from $\simeq 0.6$ below 300 MHz to $\simeq 1.1$ beyond 1.5 GHz. This variation is much faster than expected from the modified calorimeter model (Lisenfeld et al. 1996), but in agreement with synchrotron losses in an exceptionally strong magnetic field in the disk ($\simeq 20\ \mu$G on average), probably a result of interaction with the ambient intracluster medium. Field compression by ram pressure seems insufficient (Hummel & Beck 1995). Völk & Xu (1994) proposed collisions with intracluster fragments which excite shocks where particles may be accelerated.

Field enhancement and/or cosmic-ray acceleration by external influences increase the radio luminosity without enhancing the FIR emission. As a result, such galaxies exhibit a radio excess compared to the FIR at such frequencies where losses are less important and the compressed magnetic field causes enhanced synchrotron emission. Due to synchrotron losses at higher energies the enhanced emission will disappear at shorter radio wavelengths. This effect was observed in NGC 2276 by Hummel & Beck (1995). The monochromatic radio luminosity at 1.4 GHz is clearly enhanced compared to the FIR, but at higher frequencies (10.55 GHz) this radio excess is not observed anymore.

Some galaxies of the Virgo Cluster also show signs of spectral steepening. These galaxies (e.g. NGC 4438) are again strongly affected by interaction with the cluster environment (Cayatte et al. 1990) and, additionally, some of them exhibit a strong radio excess (Niklas et al. 1995b). Unusual high radio/FIR ratios have also been detected at galaxies in the Coma Cluster by Gavazzi & Contursi (1994). At the moment it remains unclear if the enhanced radio emission is due to Seyfert activity in the nuclei of these galaxies or if the interaction with the cluster environment is the reason for the spectral steepening and the radio excess. This should be subject to further investigation.

It should be noted that interacting galaxies do not necessarily show excess radio emission. The famous galaxy pair NGC 4038/39 does not show any significant deviation from the correlation (Niklas 1996). According to Menon (1991) the ratio of the radio to the FIR luminosity for spiral galaxies in a high-density environment is on average $\simeq 3\times$ *lower* than that for isolated galaxies. Nevertheless, the radio luminosities of these group galaxies are strongly correlated with the FIR luminosities. Hence, the physical conditions in the interstellar medium of these galaxies are not strongly different from those in isolated galaxies.

2.5. Galaxies with low star-formation activity

Deviations from the standard radio – FIR correlation as a *deficiency* in synchrotron emission are predicted by the calorimeter model for galaxies with low star-formation rates (CAH91, Xu et al. 1994a). The relative contribution of the 'radio-quiet', low-mass stellar population to dust heating and FIR emission increases with decreasing star-formation activity, so that the radio/FIR luminosity ratio should decrease and the radio – FIR correlation should steepen with decreasing luminosity.

The prediction by Xu et al. (1994a) concerns the mass-normalized luminosities. This cannot yet be tested with the data of Niklas et al. (1995a) because of the lack of a corresponding data set of near-infrared observations for the mass normalization. Normalization of the luminosities of the galaxies to the same absolute optical size does not change the slope of the radio – FIR luminosity correlation significantly, and a steepening at the low-luminosity end cannot be established.

According to CAH91 the most quiescent galaxies have a high optical-to-radio ratio and an important contribution of stars with masses $< 8\,\mathrm{M}_\odot$ to their interstellar radiation field. This stellar population is expected to be radio-quiet. In more active galaxies CAH91 expect more massive stars, associated with supernovae of type II and luminous HII regions, dominating the interstellar radiation field. The contribution of dust heated by these massive stars $\mathrm{L}^{\mathrm{w}}_{\mathrm{FIR}}$ to the total FIR emission $\mathrm{L}_{\mathrm{FIR}}$ of a galaxy can be evaluated using the so-called Infrared Excess IRE (Mezger 1978). The IRE gives the ratio between $\mathrm{L}^{\mathrm{w}}_{\mathrm{FIR}}$ and the Hα luminosity. The latter quantity is proportional to the thermal radio luminosity at a given thermal electron temperature (e.g. Caplan & Derharveng 1986). A detailed derivation of the ratio $\mathrm{R}_{\mathrm{w}} = \mathrm{L}^{\mathrm{w}}_{\mathrm{FIR}}/\mathrm{L}_{\mathrm{FIR}}$ based upon Hα luminosities can be found in Xu et al. (1994b).

Avoiding the extinction uncertainty of thermal radio fluxes derived from Hα fluxes, Niklas et al. (1996b) calculated the thermal fraction by analyzing the high-frequency radio continuum spectra of spiral galaxies. Using the thermal radio luminosity P_{th} at 10 GHz , R_{w} can also be expressed by (Niklas 1996):

$$\mathrm{R}_{\mathrm{w}} = 2.18 \times 10^{15} \left(\frac{\mathrm{P}^{10\mathrm{GHz}}_{\mathrm{th}}}{\mathrm{L}_{\mathrm{FIR}}} \right) \tag{1}$$

The errors in R_{w} are mainly determined by the error in the thermal radio luminosity (Niklas et al. 1996b) and are in the range of 25% to 35%. Fig. 1 shows R_{w} plotted versus the logarithm of the ratio between the blue and the radio luminosities, q_{b}, as defined by CAH91 (Eq. 15). Instead of the 1.49 GHz radio luminosities we used the 10.55 GHz luminosities given by Niklas et al. (1995a). There is no indication for active galaxies (small

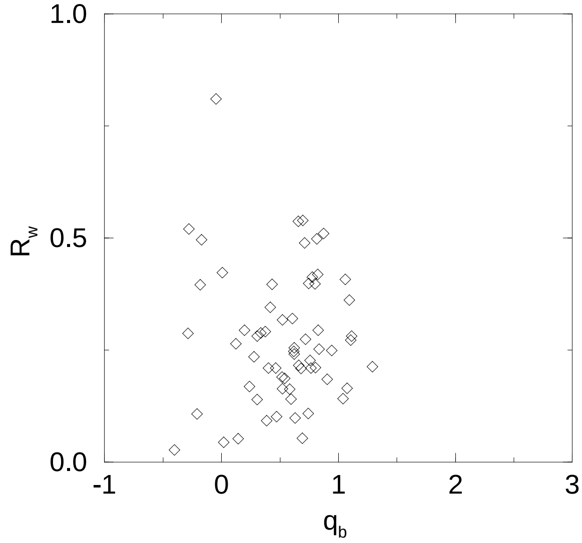

Fig. 1. The contribution of dust emission heated by young, massive stars R_w to the total FIR emission of the sample galaxies, plotted versus q_b, the logarithm of the ratio between the blue and the radio luminosities

q_b) having a higher contribution of dust heated by massive stars (large R_w) than the quiescent galaxies (correlation coefficient $<$ 0.05). Therefore, it seems unlikely that a radio-quiet FIR component in low-activity galaxies produces the non-linearity of the radio – FIR correlation. Additionally, a non-linearity of the correlation produced by low-activity galaxies implies that these are located at the low-luminosity end of the correlation. However, there also exists galaxies, especially irregular and dwarf galaxies, with relatively low L_{FIR} ($< 10^{36}$ W) but high SFE (e.g. NGC 1569), indicating strong star formation.

2.6. Summary

The presented data indicate that steep radio spectra are necessary (though not sufficient) for the 'calorimeter' assumption of efficient particle confinement. However, those steep-spectrum galaxies with magnetic field compression by interaction with an external medium deviate from the mean radio – far infrared correlation. According to the spectral analysis by Niklas et al. (1996b) $\simeq 30\%$ of the galaxies fulfill the spectral requirements for the calorimeter model. Taking into account the extension of the calorimeter model with finite escape probabilities and diffusive electron transport (Lisenfeld et al. 1996) and the uncertainties in the determination of α_{nth}, the observed radio spectra are in agreement with the conditions of the extended calorimeter model for *at most* $\simeq$ 50% of the galaxy sample. Hence, the radio – FIR correlation still has to be explained for non-calorimeter ('optically thin') galaxies.

Furthermore, the calorimeter model is unable to explain the radio – FIR correlation on kiloparsec scales which is observed in several galaxies.

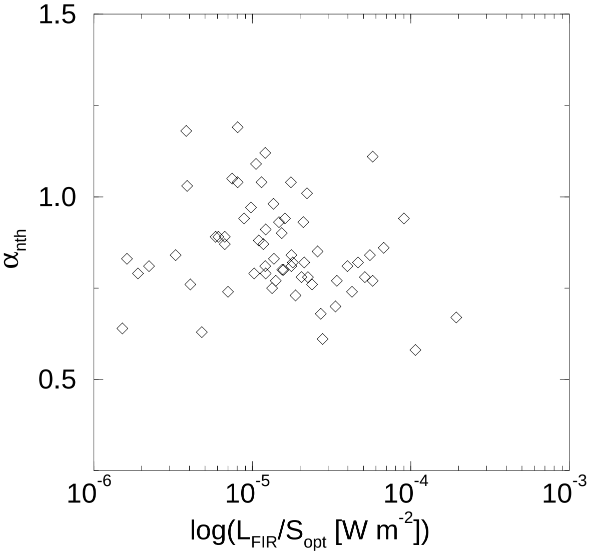

Fig. 2. The non-thermal spectral indices derived by Niklas et al. (1996b) plotted versus the FIR surface brightnesses

3. Test of the model of Helou & Bicay

According to the analysis of Wang & Helou (1992) the more luminous galaxies produce most of their infrared and radio luminosity within the same, or even smaller volume than the less luminous galaxies. Therefore a denser interstellar radiation field is expected in these galaxies. As the FIR luminosity scales with mass and size of a galaxy, it is necessary to normalize L_{FIR} in order to derive the density of the interstellar radiation field. Due to a lack of data of FIR sizes of the galaxy sample, L_{FIR} is normalised to the optical surface, which is derived from the optical major diameter D_{25} of the $25\frac{\mathrm{mag}}{\mathrm{arcsec}^2}$ isophote and corrected for inclination. In the model of Helou & Bicay (1993) the transition from galaxies with a less dense radiation field (low FIR surface brightness: $L_{FIR}/S_{opt} \lesssim 10^{-5}\ \mathrm{W\,m^{-2}}$, where S_{opt} is the surface area of the galaxy) to galaxies with a strong radiation field (high FIR surface brightness: $L_{FIR}/S_{opt} \gtrsim 10^{-4}\ \mathrm{W\,m^{-2}}$) should be accompanied by an increase in spectral index because bright galaxies should be those with strong synchrotron and inverse Compton losses (low escape probability). Fig. 2 shows that this is not the case: There is no significant correlation (correlation coefficient < 0.2) between α_{nth} and the FIR surface brightness. As mentioned above, the errors in α_{nth} are between 0.05 and 0.15. Hence, the scatter in α_{nth} can not be responsible for the absence of any correlation between α_{nth} and L_{FIR}/S_{opt}.

We then investigated the question of energy losses in a more general way. If synchrotron losses affect the spectra, we would expect a correlation between α_{nth} and the average magnetic field strength. The latter quantity was determined by assuming equipartition between the energy densities of the magnetic field and of the cosmic rays (see Sect. 4.2 for a discussion of this assumption), and a ratio k = 100 between the total cosmic-ray energy density and that of the electron component. Using the synchrotron luminosity P_{ν_0} emitted at a frequency ν_0 and

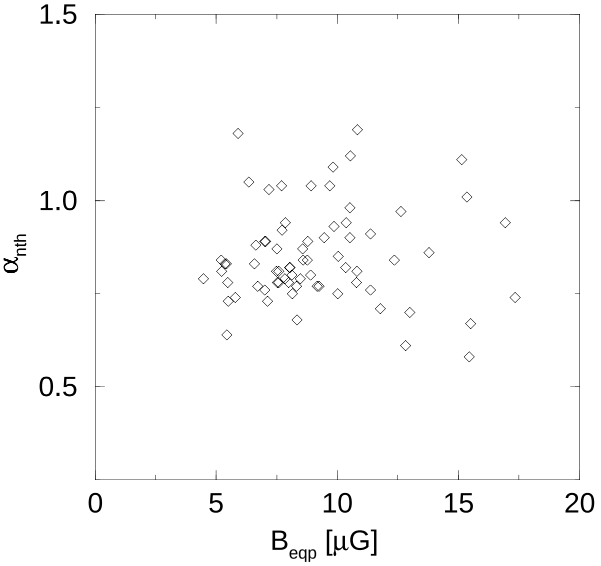

Fig. 3. Plot of the non-thermal spectral indices derived by Niklas (1995) versus the average equipartition magnetic field strengths

integrating over a fixed interval 300 MeV to infinity in cosmic-ray particle energy [1], the average equipartition magnetic field strength B_{eqp} can be evaluated:

$$B_{eqp} = \left(\frac{4\pi(\alpha_{nth} + 1)kCP_{\nu_0}\nu^{\alpha_{nth}}}{V_{sync}} \right)^{1/(\alpha_{nth}+3)} \tag{2}$$

The synchrotron emitting volume V_{sync} is defined by the optical size D_{25} and a constant disk thickness of 1.5 kpc. Previous radio surveys yield a ratio between the optical and radio size of spiral galaxies of about 0.9 to 1.3 (e.g. Hummel 1980). Only the sizes of the radio disks of some very peculiar galaxies, e.g. starburst galaxies like NGC 3034 (see discussion below) or gas-anemic cluster spirals (e.g. NGC 4569) seem to differ strongly from this average ratio. In such cases and for galaxies with very thin disks or large radio halos our assumptions lead to an error in the derived equipartition field strength. However, decreasing/increasing the disk thickness or by, for example, a factor of 3 would increase/decrease the field strength only by a factor of $3^{1/(\alpha_{nth}+3)} \simeq 1.32$. For an error about 30% in the diameter of the radio-emitting volume an error of 20% will occur in B_{eqp}. Hence, together with the error in α_{nth} (Niklas et al. 1996b) the average uncertainty in B_{eqp} is about 40% to 50%.

Fig. 3 shows the plot of α_{nth} versus B_{eqp}. One can see that no correlation exists between the two quantities (correlation coefficient < 0.1).

The non-thermal spectral indices may be additionally steepened by inverse Compton losses independent of the magnetic field. The importance of this spectral steepening in Fig. 3 has to be discussed briefly. In case of a coupling between the energy density of the interstellar radiation field and the magnetic field as suggested by Völk (1989), the steepening of the non-thermal spectra are in equal shares due to synchrotron and inverse Compton losses. Hence, a correlation between α_{nth} and the average magnetic field strength is not destroyed by spectral steepening due to inverse Compton losses. This can only happen if inverse Compton losses are very high in galaxies with low magnetic fields, so that any spectral steepening for these galaxies would only be due to inverse Compton scattering. This would require that the interstellar radiation field is high in galaxies with low magnetic field strengths B. However, the correlation found between B and L_{FIR} (see Sect. 4) indicates that this is not the case. Hence, the absence of a correlation between α_{nth} and B cannot be the result of different amounts of synchrotron and inverse Compton losses at different magnetic field strengths.

In the case of strong energy losses of the electrons, the electron spectral index is different from that of the cosmic-ray protons, so that the integrated energy density of the electrons is no longer $1/k$ of the total cosmic-ray energy density, as is generally assumed (Pohl 1993). This leads to an overestimate of the equipartition field strength by a factor of 2 or more. (We note that, as a consequence, equipartition field strengths are *always* overestimated in the calorimeter model.) Taking this effect into account, points in Fig. 3 with $\alpha_{nth} > 0.9$ (strong synchrotron losses) should be shifted to lower field strengths, which would not improve the correlation.

A special case is the galaxy NGC 3034 (M 82). According to Klein et al. (1988) the synchrotron emission of this active galaxy is concentrated to a small region in the centre. Our general assumption of the synchrotron volume of the galaxies leads to a radio – emitting volume of M 82 which is too large. Hence, our derived magnetic field strength is too low. Together with the flat synchrotron spectrum of M 82 ($\alpha_{nth} = 0.67 \pm 0.02$) the lack of a correlation between magnetic field strength and particle confinement is confirmed in this case.

We conclude that the variations in synchrotron spectra are due to *both* energy-loss processes and propagation properties of the cosmic-ray electrons, so that spectral indices correlate neither with the density of the radiation field as measured by the FIR surface brightness nor with average field strength. The combined effects of star formation and the strength and structure of the magnetic fields determine the diffusive and/or convective escape of cosmic-ray electrons.

4. A new approach

From the analysis of the galaxy survey data by Niklas et al. (1995a) we conclude that a large fraction of spiral galaxies do not behave like calorimeters, so that most of the cosmic-ray electrons escape without significant synchrotron or inverse Compton losses. On the other hand, our data are also in conflict with the optically-thin model of Helou & Bicay (1993). Furthermore, there is strong evidence that galaxies are optically thick for UV photons (Xu & Buat 1995), so that a coupling between

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[1] The standard procedure uses a fixed integration interval in radio frequency which corresponds to different intervals in cosmic-ray particle energy, depending on the average magnetic field strength which varies between galaxies. Integration over a fixed energy interval avoids this hidden dependence.

electron escape and optical thickness cannot explain the radio – FIR correlation for non-calorimeter galaxies. A new model is required.

The radio – FIR correlation is one of the tightest relations known in astrophysics. The underlying physics must be valid even under strongly varying conditions, without invoking many parameters. If galaxies are optically thick for UV photons, but ‘optically thin’ for cosmic-ray electrons, there is need neither for a correlation between the energy densities of the magnetic field and the radiation field, nor for a correlation between optical depth and escape probability.

We propose that the radio – FIR correlation is the consequence of several more basic physical relations which are known to hold in galaxies, or are at least highly probable.

4.1. Magnetic field strength and gas density

One clue to the understanding of the radio – FIR correlation is the relation between the average magnetic field strength B and the average volume density of the cool, (almost) neutral gas ρ in a galaxy, thus adopting one of the assumptions of Helou & Bicay (1993).

A relation between B and ρ has been found from data with various spatial resolutions, e.g. in a spiral arm region southwest of the M 31 centre (Berkhuijsen et al. 1993) as well as in the Milky Way (Berkhuijsen, in prep.). A similar relation may be valid universally from smallest (Fiebig & Güsten 1989) to largest cosmic scales (Vallée 1990). Here we show that such a relation is also valid on global galactic scales.

For 43 galaxies we could determine the equivalent volume densities $\rho_{\rm eqv}$ for the total cool gas, using the HI masses of Huchtmeier & Richter (1989) and the H_2 masses of Young et al. (1989) and Solomon & Sage (1988). The volume densities of the neutral hydrogen and the molecular hydrogen are calculated individually. Then, the equivalent volume density of the cool gas $\rho_{\rm eqv}$ was computed by averaging the volume densities of the individual gas components. The H_2 masses of Solomon & Sage (1988) were scaled to the $N(H_2)/I_{\rm CO}$ conversion factor used by Young et al. (1989). According to Young et al. (1989) the typical errors in the CO fluxes are between 20% and 30%. Individual errors for the H_2 masses are are given neither by Solomon & Sage (1988) nor by Young et al. (1989). Errors of the HI masses are given for some galaxies (Huchtmeier & Richter 1989). They range from 10% to 25%.

The gas volume of each galaxy was assumed to be an oblate ellipsoid with the major axis equal to half the optical diameter D_{25} and the minor axis equal to a constant scale height. The scale heights used for HI and H_2 gas were 1 kpc and 0.5 kpc, respectively. The use of a major axis of 2 or 3 × D_{25} may be more realistic, but this would only shift all points by the same amount towards lower equivalent gas volume densities. Additionally, galaxies which are known to be gas-poor or anemic (e.g. NGC 4438) are excluded from this analysis.

Fig. 4 shows the plot of the equipartition magnetic field strength $B_{\rm eqp}$ versus the equivalent gas volume density $\rho_{\rm eqv}$. The best-fit slope, obtained by the ‘bisector method’ of Isobe et al. (1990), is m = 0.48 ± 0.05 with a correlation coefficient of 0.67. The slope is in agreement with values of the magnetic field–gas density correlation in M 31 and the Milky Way.

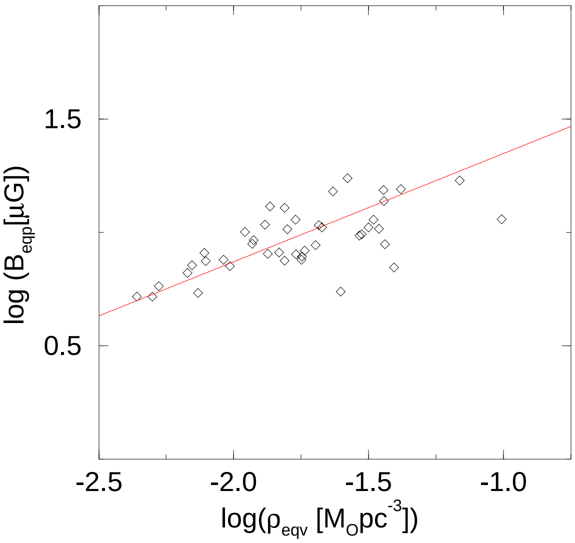

Fig. 4. The average equipartition magnetic field strengths plotted versus the average equivalent volume densities of the cool gas $\rho_{\rm eqv}$. The solid line represents the best fit to the data. Its slope is m = 0.48 ± 0.05.

The relation between B and ρ is expected to break down on scales smaller than the average distance between gas clouds, i.e. below a few 100 pc.

4.2. Equipartition between the cosmic-ray and magnetic field energy densities

The energy densities of cosmic rays and magnetic field are generally assumed to be proportional (equipartition or minimum total energy). In this case, the synchrotron emissivity (i.e. luminosity per unit volume) is given by $\epsilon_{\rm sync} \propto B_{\rm eqp}{}^{(\alpha_{\rm nth}+3)}$. Although the equipartition argument has been controversely discussed, a comparison of magnetic field strengths derived using the equipartion assumption with field strengths using other methods (Faraday rotation, γ-ray emission) by Vallée (1995) gave an agreement between the derived values within 20 %. From the observed radio morphologies of galaxies strong deviations from equipartition can be excluded on large spatial scales (Duric 1990).

Cosmic rays are continuously supplied by sources in the galactic disk and propagate out into the halo by diffusion and/or convection (galactic wind). (Detailed propagation models have been presented e.g. by Pohl & Schlickeiser (1990a,b).) As in our model the cosmic-ray electrons responsible for the observed synchrotron emission are not loss-dominated, their energy density is a (constant) fraction of the total energy density of the cosmic rays, which is determined by the field strength alone. Under such a steady-state condition, neither the cosmic-ray production rate nor the escape probability affects the energy density of the particles and the synchrotron luminosity. While on small spatial scales, e.g. in supernova remnants, the energy density of the particles may exceed strongly the energy density of the magnetic field, the components of the interstellar medium have been relaxed on larger scales (e.g. determined by the height of the layer of gas clouds of a few 100 pc) and the energy densities should approach equipartition. The local radio – FIR correlation should break down on small time and spatial scales where equipartition is not valid anymore.

4.3. Far infrared luminosity and star formation

The far infrared luminosity L_{FIR} as well as the FIR surface brightness on kpc scales are linearly proportional to the star-formation rate (SFR) over a time scale of $\simeq 10^8$y: Buat (1992) found that the surface brightnesses in Hα and FIR in galaxies are linearly proportional, and the thermal radio luminosity and the FIR luminosity are linearly related (Price & Duric 1992, Niklas 1996). However, this may no longer be true for galaxies where dust heating by the radiation field of low-mass stars dominates (Xu et al. 1994a, Smith et al. 1994) and the FIR emission traces SFR over the last $\simeq 10^9$y.

We also conclude from the results of Buat (1992) that the stellar initial mass function (IMF) is constant over the time scale of $\simeq 10^8$y as well as from galaxy to galaxy. Furthermore, any dependence of the IMF on the average magnetic field strength as proposed by Mestel (1994) has to be small.

In spiral galaxies with continuous SFR the relation between L_{FIR} and SFR may be assumed to hold on a time scale of $\simeq 10^9$y, thus including also the contribution of low-mass stars to the FIR emission. Although the synchrotron lifetime of GeV electrons in a 10μG magnetic field is only a few 10^7y, the radio – FIR correlation holds on a longer time scale because the cosmic-ray particles are continuously supplied (see Sect. 4.2).

An increase of SFR in localized regions on small time scales will only affect the contribution to L_{FIR} from high-mass stars, not the synchrotron luminosity. Again, local deviations from the radio – FIR correlation are to be expected, i.e. the ratio of the radio to the FIR flux density becomes smaller than average. This is observed in the central regions of galaxies (Beck & Golla 1988, Bicay & Helou 1990).

4.4. Schmidt law

The star-formation rate SFR follows a 'Schmidt law' (Schmidt 1959), i.e. SFR $\propto \rho^n$:

A correlation between SFR derived from the Hα emission and *surface* density of the total gas was investigated e.g. by Kennicutt (1989) who found $n_{surf} = 1.3 \pm 0.3$. The use of UV, FIR and radio continuum surface brightnesses as star-formation indicators yielded similar results (Buat 1992): depending on the star-formation indicator, the slope of these correlations are between 1.0 and 1.5. The typical errors of these slopes are about 0.15. This supports the existence of a correlation between SFR and gas density on a time scale of $\simeq 10^8$y. For smaller time scales, Dopita & Ryder (1994) found $n_{surf} \simeq 1.5$ for their best-fit model based on their Hα data, but need another (weaker) dependence on the surface density of the total mass.

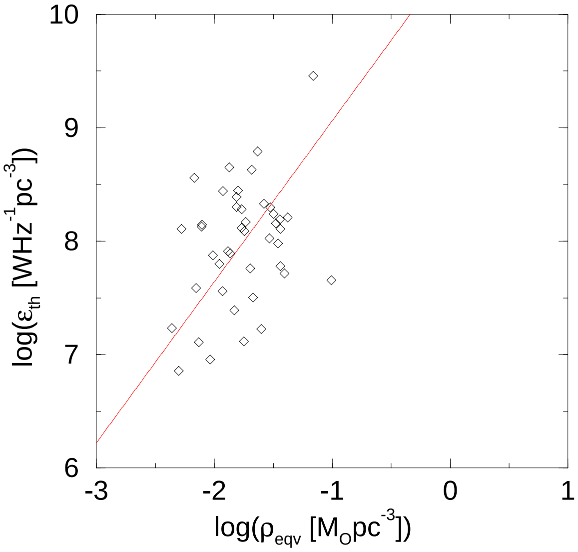

Fig. 5. The thermal radio emissivities ϵ_{th} plotted versus the average equivalent volume densities of the cool gas ρ_{eqv}. The solid line represents the best fit to the data. Its slope is m = 1.4 ± 0.3.

Thermal radio emission is produced by free-free emission of thermal electrons in HII regions heated by young, massive stars. Like the Hα emission it is proportional to the emission measure which is the square of the thermal electron density integrated along the line of sight. Therefore, the thermal radio luminosity can be used as an indicator for at least the recent star formation (time scale $\simeq 10^7$y), but may be used also for longer time scales, as normal spiral galaxies do not show strong time variations in their star-formation rates. Furthermore, Dopita & Ryder (1994) found that the intensities of the Hα emission and the I-band emission from old stars are proportional to each other.

For galaxies with known ρ_{eqv} the thermal radio luminosities were extracted from the radio survey data (Niklas 1995, Niklas et al. 1995a). These thermal luminosities were normalized by the radio-emitting volume of the galaxies. The volume was calculated as described for the calculation of the equipartition magnetic field strengths. The adopted scale height was 1.5 kpc. This equivalent thermal emissivity ϵ_{th}, used as a measure of the SFR, is plotted versus ρ_{eqv} (Fig. 5). The best-fit slope is $n_{vol} = 1.4 \pm 0.3$ with a correlation coefficient of 0.49. The large scatter in the relation reflects the difficulties in separating the thermal and non-thermal emission using the integrated radio spectra[1].

Similar to the other relations of our approach, the Schmidt law may be invalid for localized regions on short time scales, i.e. if the gas density (and the magnetic field) is enhanced by compression. This leads to an immediate increase of the radio

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[1] As for each galaxy the same scale height was used, the obtained relationship is effectively a relation between surface densities. The slope is then in good agreement with those derived by Kennicutt (1989) and Buat (1992) from optical data.

synchrotron emission and thus to a deviation from the radio – FIR correlation, as observed in a few interacting galaxies (see Sect. 2.4).

The Schmidt law is invalid for gas densities smaller than the threshold below which no star formation is possible.

4.5. Summary

Using the results of Figs. 4 and 5, we have $B_{eqp} \propto {\rho_{eqv}}^{0.48\pm0.05}$ and $SFR \propto {\rho_{eqv}}^{1.4\pm0.3}$, which yield $SFR \propto {B_{eqp}}^{2.92\pm0.70}$ or $B_{eqp} \propto SFR^{0.34\pm0.08}$. This is significantly different from the result obtained by Vallée (1994), who used fewer galaxies and only Hα data as a measure of SFR. The assumed proportionality between SFR and L_{FIR} then gives the relation $B_{eqp} \propto L_{FIR}^{0.34\pm0.08}$. A plot of the derived equipartition field strength versus L_{FIR} yields a slope of 0.38 ± 0.03, which is in good agreement with the expected value, with a correlation coefficient of 0.62.

The non-thermal radio – FIR correlation can now be evaluated by using the relation between the synchrotron luminosity and the average equipartition magnetic field strength, $P_{sync} \propto B_{eqp}^{\alpha_{nth}+3}$. We replace B_{eqp} by ρ_{eqv}^{m}, use the Schmidt law $\rho \propto SFR^{1/n}$ and the linearity between SFR and L_{FIR}. This yields $P_{sync} \propto L_{FIR}^{x}$ with the following exponent:

$x = m \cdot (\alpha_{nth} + 3)/n.$

Using the observed average non-thermal spectral index of spiral galaxies ($\langle\alpha_{nth}\rangle = 0.85 \pm 0.02$, Niklas et al. 1996a), the slope of the magnetic field strength–gas density relation ($m = 0.48 \pm 0.05$, Fig. 4) and the relation between the SFR and the volume density of the cool gas ($n_{vol} = 1.4 \pm 0.3$, Fig. 5) it follows that

$x = 1.32 \pm 0.29.$

This is in excellent agreement with the results of the analysis of the observed radio – FIR luminosity correlation presented by Niklas (1996) which gives $x = 1.25 \pm 0.08$. The relations between the different quantities are illustrated in Fig. 6.

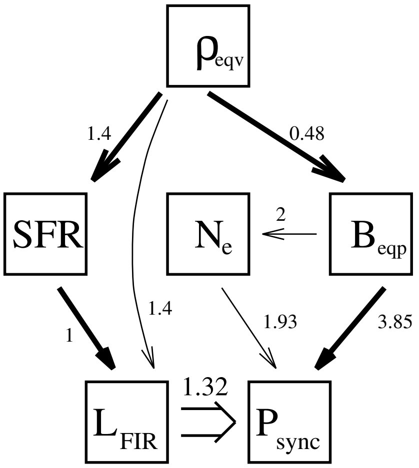

Fig. 6. Diagram of the relations between the different parameters controlling the radio – far infrared correlation. The *observed* correlations (thick arrows) are between the volume density of the cool gas ρ_{eqv}, the star-formation rate SFR and the strength of the equipartition magnetic field B_{eqp}, and between SFR and L_{FIR}. Validity of equipartition between the energy densities of the cosmic rays and of B is assumed. The correlation follows from these relations.

5. Discussion

We propose that the physical background of the radio – FIR luminosity correlation is the dependence of both the magnetic field strength and the star-formation rate on the volume density of total cool gas. These relations are well founded by observations. They provide a simple and global model, as is required by the universality and tightness of the radio – FIR correlation. The gas clouds are thus the primary factor controlling the physics of the interstellar medium. The tight radio – FIR correlation is a byproduct.

A model of the coupling of magnetic field lines to cool interstellar gas clouds has been presented by Parker (1966), based on the concept of dynamical instabilities. Even a low degree of ionization suffices to anchore the field lines in gas clouds. Enhanced turbulent motion and collisions of the clouds may explain the observed strong field tangling in spiral arms (Beck 1991). On large and global scales, ρ is a measure of the *number density of gas clouds* rather than a measure of their internal gas density. Hence, our relation between B and ρ does not mean that the field is compressed in a collapsing cloud, but indicates that the number of field lines increases with decreasing distance between clouds, in agreement with magnetic flux conservation. Such a 'compression' of the 'fluid' of gas clouds also explains the observed increase of the total field strength in spiral arms (Berkhuijsen et al. 1993). Dynamo theory predicts a similar relation between gas density and field strength if the field amplification is limited by magnetic stresses or by turbulent motion of gas clouds (e.g. Ruzmaikin et al. 1988). Hence a close coupling between field lines and gas clouds seems reasonable, though a detailed theory is still lacking.

While the amount of gas limits the magnetic flux which can be stored in a galaxy, the magnetic flux limits the number of cosmic-ray particles which can be stored in the galaxy, as long as they are continuously supplied. Excess particles will leave the galaxy, so that energy equipartition between magnetic field and cosmic rays is preserved. The resulting number density of interstellar cosmic-ray particles per energy interval N_e thus scales with B_{eqp}^2, with $\rho_{eqv}^{0.96\pm0.10}$ and with $SFR^{0.69\pm0.07}$, while their production rate may still scale linearly with SFR, as generally assumed.

The non-linearity of the non-thermal radio – FIR correlation follows naturally from the relations between the quantities controlling the correlation. In contrast to other models (e.g. CAH91, Fitt et al. 1988, Devereux & Eales 1989) we do not have to correct for this non-linearity. As a consequence we do not expect any change in slope x of the non-thermal radio – FIR correlation, and the ratio $q = \log(L_{FIR}/P_{sync})$ (as defined by CAH91) should continuously decrease with SFR, $q \propto (x - 1)\log(1/SFR)$. Asymptotic values for q at large and small SFR (see CAH91) would lead to a non-constant slope x. A change in slope x is crucial for any model in which the non-linearity is attributed to different amount of FIR emission originating in massive star-forming regions to the total FIR luminosity. Unfortunately, on the basis of the existing data of separated thermal and non-thermal radio emission, changes in slope can not be significantly ruled out because the dynamical range in luminosity is too small. Including galaxies at the extreme ends of the luminosity ranges are required for deciding this question.

However, the results shown in Fig. 1 indicate that the contribution of massive stars to dust emission is not coupled to the activity of the galaxies. If a variation in the efficiency of cosmic-ray confinement were responsible for the non-linearity, one would expect a systematical change in slope from low radio frequencies (where the particle escape probability is high) towards high radio frequencies (where the particle trapping is more efficient). Such a change in slope from 151 MHz up to 10 GHz is *not* observed (Fitt et al. 1988, Devereux & Eales 1989, Niklas 1996).

Our new approach is the first one able to explain the radio – FIR correlation on smaller than global scales because only the local gas density counts. We predict that the correlation should break down on scales smaller than the average distance between clouds. On scales below a few 100 pc all the relations essential for our approach (Sects. 4.1–4.4) can be violated so that the correlation does not hold anymore. Indeed, the correlation is no longer valid on scales smaller than a few hundred parsecs around regions of star formation in our Galaxy (Boulanger & Pérault 1988). We also predict that the correlation does no longer hold outside the disk of gas clouds. This scenario can be tested with FIR data from the ISO satellite.

If the star-formation rate were the driving force, the radio – FIR correlation should break down at low FIR luminosities where the 'radio-quiet' FIR component dominates (Xu et al. 1994a). Our approach, however, may also be applied to low-luminosity galaxies as long as SFR is constant over $\simeq 10^9$y, so that the radio – FIR correlation is still valid at low FIR luminosities, in accordance with observations. In galaxies with low $L_{\rm FIR}$ (e.g. M 31, Walterbos & Schwering 1987) there is still significant synchrotron emission because it is coupled to gas density, not to SFR. The correlation should break down only if the star-formation rate (or gas density) falls below some critical value, so that the production of cosmic-ray electrons becomes too low to maintain the equipartition condition. This is should be investigated in more detail with the new ISO data.

The tightness of the radio – FIR correlation requires that the underlying basic correlations with gas density are even tighter. This gives little room for other parameters possibly influencing the star-formation rate but not connected with magnetic fields, like the gravitational potential of the stars. As a consequence, the relatively large scatter in Figs. 4 and 5 should be only partly intrinsic, but mostly due to uncertainties in the determinations of ρ, B and SFR. Clearly, more and better data are needed.

The radio – FIR luminosity correlation is a powerful tool to investigate the physics of the interstellar medium. Deviations from the correlation indicate that either external forces modify the magnetic field structure (in case of interacting galaxies), or that the underlying process of the radio emission is not star formation but produced by a single central engine (as in the case of galaxies with Seyfert nuclei), or that the average star-formation rate in a galaxy varies strongly on time scales below $\simeq 10^8$y.

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