N87-24351

THE RADIO-FAR INFRARED CORRELATION: SPIRAL AND BLUE COMPACT DWARF GALAXIES OPPOSED

U. Klein
Radioastronomisches Institut der Unversität Bonn
F.R.G.

E. Wunderlich
Max-Planck-Institut für Radioastronomie
F.R.G.

Abstract: The recently established correlation between radio continuum and far infrared emission in galaxies has been further investigated by comparing normal spiral and blue compact dwarf galaxies. The puzzling result is that the ratio of radio-to-far infrared luminosity and its dispersion is the same for both samples, although their ratios of blue-to-far infrared luminosity, their radio spectral indices and their dust temperatures exhibit markedly different mean values and dispersions. This suggests that the amount of energy radiated in the two regimes is enhanced in the same way although the mechanisms responsible for the two components are rather different and complex. The fact that the blue light does not increase at the same proportion shows that both the radio and the far infrared emission are connected with the recent star formation history.

1. INTRODUCTION

Soon after the successful IRAS mission, several groups of investigators reported a close correlation between the integrated radio continuum and far infrared (FIR) emission from galaxies, with the radio continuum radiation being predominantly of nonthermal origin (de Jong et al., 1985, Helou et al., 1985, Sanders and Mirabel, 1985). The most straight-forward interpretation was in terms of a close connection between dust heating and cosmic ray production via recent star-forming activity. Hummel (1986), investigating this correlation for a sample of Sbc galaxies, considered this relation as evidence for the validity of energy equipartition between cosmic rays and magnetic fields in Sbc spiral galaxies, with a uniform star formation rate during the past $\sim 10^9$ yrs.

A similar investigation was carried out by Kunth and Sevre (1986) for a sample of blue compact dwarf galaxies (BCDGs), and again drawing the attention to the amazingly tight correlation between radio and FIR emission, holding even for this outstanding class of galaxies.

In order to investigate this intriguing and puzzling correlation further, we have undertaken a comparison of the total radio and FIR emission from normal spiral galaxies (NSGs) and BCDGs.

2. THE SAMPLES AND THE DATA

Radio continuum measurements of BCDGs have been accumulating during the past decade, obtained primarily with single dishes (see the compilation of Klein, 1986). In some cases measurements at two or more frequencies exist so that (more or less accurate) spectral indices can be derived. Recently high-resolution VLA observations have been carried out by several groups of investigators (e.g. Brinks and Klein, 1986, Wynn-Williams and Becklin, 1986, Sramek and Weedman, 1986) which, besides allowing more detailed studies, are indispensable as a check on the confusion problems naturally inherent to the single-dish measurements. Some 40 BCDGs have so far been detected in the radio continuum (mainly at 5 GHz), and for a few of them upper limits have been obtained. For nearly 30 of them spectral indices could be derived, but nearly half of these are still rather unreliable. All of the flux densities incorporated in the present work have been taken from the above-mentioned literature, supplemented by more recent measurements carried out with the Bonn 100-m telescope (Klein, in prep.). FIR flux densities of the BCDGs have been compiled by Kunth and Sevre (1986), in addition the work of Gondhalekar et al. (1986) and of Wynn-Williams and Becklin (1986) provided some more data. Blue optical magnitudes have been adopted from the list of Thuan and Martin (1981). All of the BCDGs for which radio continuum measurements exist have been used for the present analysis. This 'sample selection' may therefore bear the danger of being biased, but selection effects would probably have been more serious if the sample had been chosen using FIR detections.

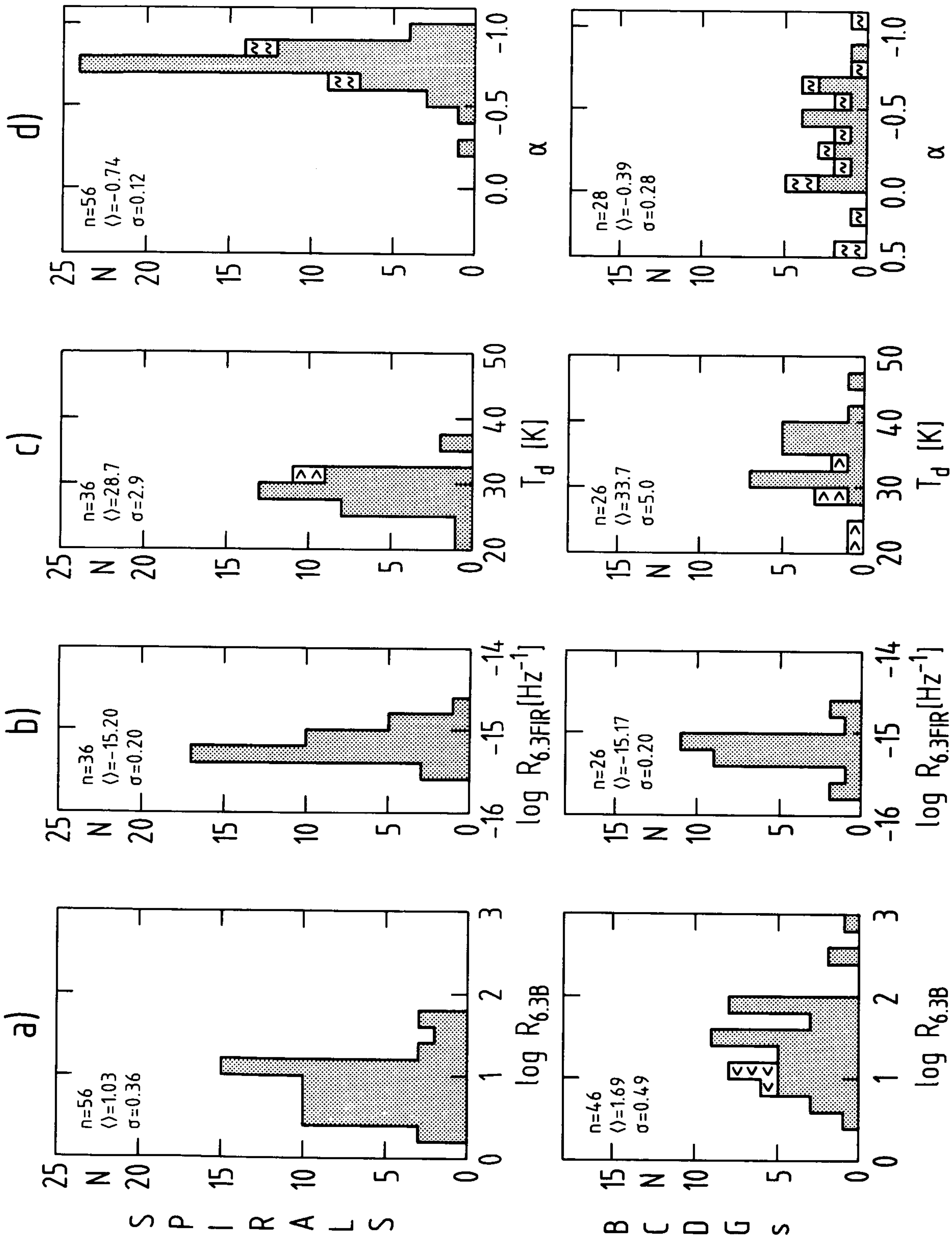
As a comparison sample to represent what one would call normal spiral galaxies (in the sense that they have seen a uniform history of star formation over at least the past $\sim 10^9$ yrs) we have chosen that investigated by Gioia et al (1982) for which accurate flux densities over a wide frequency range and therefore reliable spectral indices, are available. The FIR data have been taken from the following sources: for all of the galaxies which are smaller than the detector sizes (i.e. galaxies with angular extents smaller than about 6') the data have been taken from the IRAS Point Source Catalogue (PSC). For those galaxies which have sizes between about 6' and 8' the data have been taken from the Small Scale Structure Catalogue, while galaxies larger than that have been analyzed in the IRAS maps of the HCON1 survey. The blue magnitudes of the NSG sample have been adopted from the list of Gioia and Gregorini (1980).

We have thus complete radio and optical data for the two samples investigated here. FIR data (and spectral indices in case of BCDGs) are available for only about 60% of the galaxies.

3. INTEGRATED RADIO AND FIR PROPERTIES

In Figure 1a-d we present all of the properties relevant to the current analysis for NSGs (upper row) and BCDGs (lower row). Some of the properties have already been derived and discussed previously: it is known that the radio index (ratio of radio-to-optical luminosity) of BCDGs is significantly higher than that of NSGs, and that the average radio spectrum of BCDGs is much flatter than that of NSGs (see Klein et al., 1984). Here we have supplemented the previously existing radio data with the more recent measurements mentioned in Section 2. High-resolution observations with the VLA (see e.g., Brinks and Klein, 1986) at λ20 cm and λ6 cm revealed that some of the single-dish fluxes were confused by nearby unrelated sources. The updated distributions of the radio index at λ6.3 cm, $R_{6.3B}$, and the spectral index, α *, are plotted in Figures 1a and d. Hyphens indicate spectral index uncertainties in excess of 0.2. Figures 1b and c display those histograms which incorporate the FIR data from the PSC. The ratio

* $R_{6.3B} = S_{6.3}\ \mathrm{dex}\ ((m_B-12.5)/2.5) = 0.044\ S_{6.3}/S_B$, where $S_{6.3}$ and S_B are in mJy and $S_\nu \sim \nu^\alpha$


a)
b)
c)
d)
SPIRALS
BCDGs
n=56
⟨⟩=1.03
σ=0.36
n=46
⟨⟩=1.69
σ=0.49
n=36
⟨⟩=−15.20
σ=0.20
n=26
⟨⟩=−15.17
σ=0.20
n=36
⟨⟩=28.7
σ=2.9
n=26
⟨⟩=33.7
σ=5.0
n=56
⟨⟩=−0.74
σ=0.12
n=28
⟨⟩=−0.39
σ=0.28
N
log R6.3B
log R6.3FIR [Hz−1]
Td [K]
α

$R_{6.3FIR}$ of radio-to-FIR luminosity is shown in Figure 1b, the dust temperature in Figure 1c. The latter was derived from the ratio of the 100μ-to-60μ flux densities and by assuming an $F_\nu \sim \nu^{1.5} \cdot B_\nu(T_d)$ dust emission law. The ratio $R_{6.3FIR}$ was derived by computing the FIR luminosity using the 100μ and 60μ flux densities which reflect the bulk of the FIR luminosity and following the procedure of Helou et al. (1985). This ratio is then obtained as

$$\log R_{6.3FIR} = -15.10 + \log S_{6.3} - \log(2.58\, S_{60} + S_{100}),$$

where $S_{6.3}$ is in mJy and S_{60} and S_{100} are in Jy. All of the mean values and standard deviations given in each figure have been obtained by properly weighting the individual data.

Let us first turn to the spectral indices, obtained by applying least-squares fits to the data. As discussed by Gioia et al. (1982) the distribution of α for NSGs is extremely narrow indicating that both the nonthermal spectral indices (α_{nt}) as well as the thermal/nonthermal ratios ($f_{tnt}(\nu)$) do not vary among NSGs. This certainly does not hold for BCDGs for which (in spite of the large uncertainties still inherent to the data) the spectral indices show a large scatter around a mean value, which as stated already by Klein et al. (1984) suggests significantly flatter spectra for these than for NSGs. The strong 'thermal' wing in Figure 1d near $\alpha = 0$ indicates that thermal emission plays a major role in this galaxy type, but the spread of α down to about -0.8 implies that probably all combinations of α_{nt} and $f_{tnt}(\nu)$ may occur, in particular nonthermal spectra which may be <u>flatter</u> than those derived for NSGs.

There is also a pronounced difference between the distributions of dust temperature of NSGs and BCDGs: BCDGs appear to host much warmer dust on average than normal spirals do. The same conclusion had already been reached by Helou (1986) who compared samples of BCDGs and Virgo spirals. Another interpretation would be a lack of the cooler dust component in BCDGs which according to Cox et al. (1986) delivers about 40% of the total luminosity of the dust emission in the Milky Way. This cooler dust component, with a temperature range of $T_c \sim$ 15-25 K (note that Cox et al. used an $F_\nu \sim \nu^2 \cdot B_\nu(T_d)$ law), is associated with atomic hydrogen and heated by the general interstellar radiation field (ISRF), while the warm dust component has $T_c \sim$ 30 - 40 K and is associated with ionized gas in extended low-density (ELD) HII regions and heated by OB stars. According to Figure 1c this latter component contributes a much larger fraction to the total FIR emission in BCDGs than in NSGs, which once again emphasizes their similarity to HII regions, as was first pointed out by Sargent and Searle (1970). In addition the dust temperatures in BCDGs appear to occupy a wider range than those of NSGs.

What about the radio continuum - FIR relation? Looking at Figure 1b we immediately realize that there is <u>no difference at all</u> between BCDGs and NSGs, <u>neither</u> in the <u>mean values nor</u> in their <u>standard deviations</u>! This is a puzzling result: it means that regardless of what is the predominant mechanism of dust heating (OB stars in ELD HII regions or the ISRF for the diffuse component) and regardless of what is the thermal/nonthermal ratio and the energy spectrum of cosmic ray electrons, the ratio of radio-to-FIR luminosity is universal! Both (thermal and nonthermal) radio as well as thermal emission from dust must therefore be enhanced in the same way as the star formation activity increases. This obviously applies only to the recent star formation history, since otherwise we would expect the blue light to increase by about the same proportion, which according to Figure 1a it does not.

It is remarkable that IZw18 and IIZw40, the BCDGs with the most extreme properties (they are particulary metal-poor and exhibit very high gas contents, IIZw40 has the highest radio index and the highest dust temperature) are well within the distribution of radio-to-FIR luminosity.

4. CONCLUSIONS:

It is puzzling that the two emission processes ((thermal and nonthermal) radio and FIR) which arise from very different mechanisms apparently follow the same relation and probably increase at the same rate as the star formation rate increases. The predominant dust heating process apparently has no influence on the total amount of FIR emission, and neither has the thermal/nonthermal ratio and the nonthermal radio spectrum on the total amount of radio radiation.

The lack of scatter in the radio-to-FIR ratios of BCDGs suggests that (at least in this galaxy type) the (thermal and nonthermal) radio emission must be connected with the most recent star formation as already stated by de Jong et al. (1985) because the - undoubtedly rapidly varying - star formation history in BCDGs would otherwise have resulted in a variation of this ratio. Hence this ratio is not very suitable for studying variations in recent star formation histories. The situation must be different for NSGs: under normal conditions (i.e., in the absence of tidal interactions, strong bars, etc.) their star formation rates did not vary over the last $\sim 10^9$ yrs. (Larson and Tinsley, 1978). Therefore the lack of scatter in the radio-to-FIR luminosity ratio of NSGs was to be expected. The larger scatter in the ratio of radio-to-optical luminosity for NSGs can be explained in terms of varying star formation rates before that epoch, since the blue light is about equally shared by stars younger and older than that. Consistent with this, the scatter in the radio-to-optical luminosity ratio of BCDGs is somewhat larger than that of NSGs because in these the relative contribution of young stars to the blue light is much higher than in NSGs so that the scatter of $R_{6.3B}$ partly reflects the violent recent star formation epoch.

We can finally rule out any obvious underabundance of dust in BCDGs as compared to NSGs because we would otherwise expect lower values of $R_{6.3FIR}$ for the former, or at least a wing of lower values. Normal amounts of dust in BCDGs would then contradict the view of them being 'young' galaxies (in the sense that most of them are undergoing their first burst of star formation).

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