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THE FAR-INFRARED/RADIO CORRELATION OF STARBURST GALAXIES: CONSTRAINTS ON THE MAGNETIC FIELD

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RESUMEN

Se investiga la correlación entre el IR lejano y la emisión de radio en galaxias con brotes de formación estelar. Se analizan y comparan datos de galaxias en interacción y galaxias normales, a la vez que se ha desarrollado un modelo para la emisión en IR lejano y en radio. Este modelo indica que para explicar la relación constante que se observa entre el IR lejano y el radio es necesario un fuerte y rápido ($\approx 10^7$ años) aumento del campo magnético al comienzo de un brote de formación estelar. Se discuten los posibles mecanismos que relacionan la actividad de formación de estrellas y el campo magnético.

ABSTRACT

The correlation between the far-IR (FIR) and the radio emission of starburst galaxies is investigated by analysing and comparing data for interacting and normal galaxies, and by modeling the FIR and the radio emission during a starburst. The model shows that a strong and fast ($\approx 10^7$ years) increase of the magnetic field at the beginning of the starburst is required in order to reproduce the observed constancy of the FIR/radio ratio. The possible mechanisms relating the star formation activity and the magnetic field strength are discussed.

Key words: **GALAXIES: MAGNETIC FIELDS — GALAXIES: STARBURST — INFRARED: GALAXIES — RADIO CONTINUUM: GALAXIES**

1. INTRODUCTION

Starburst galaxies are found to follow the tight correlation between the far-infrared (FIR) and the radio emission (e.g., van den Driel et al. 1991). Here, the correlation is even more unexpected than in normal galaxies because of the following reasons. In starburst galaxies the different time-scales involved in the production of the radio and the FIR emissions become important: Whereas the FIR emission and the thermal radio emission are instantaneously related to the stellar radiation, the synchrotron emission shows a time delay because it takes some 10^6 yr until the first supernovae (SNe) occur, and some 10^7 yr till the maximum of SN activity is reached. These time-scales are comparable to the duration of starbursts of about $10^7 - 10^8$ yr and should therefore result in a time delay between the maximum emission of the FIR and the radio emission. Furthermore, during a starburst the intensity of the radiation field changes with time in a significant way. Little is known about variations of the magnetic field energy density. The ratio of these two parameters that determine the major radiative losses of the cosmic ray (CR) electrons (inverse Compton and synchrotron losses) is crucial for the total synchrotron emission of a galaxy.

The aim of this work is to understand why, in spite of the above considerations, the FIR/radio ratio is observed to be very constant in starburst galaxies, and, more importantly, to use this observational fact to find constraints for starburst models. For this purpose data for interacting galaxies, many of which are undergoing a starburst, and for normal galaxies have been analysed and compared in order to test for any difference between starburst and normal galaxies and in order to see whether the FIR/radio ratio depends on the starburst strength. Furthermore, a model for the FIR and the radio emission in a starburst was developed in order to interpret the observational results (see Lisenfeld et al. 1996 for more details).

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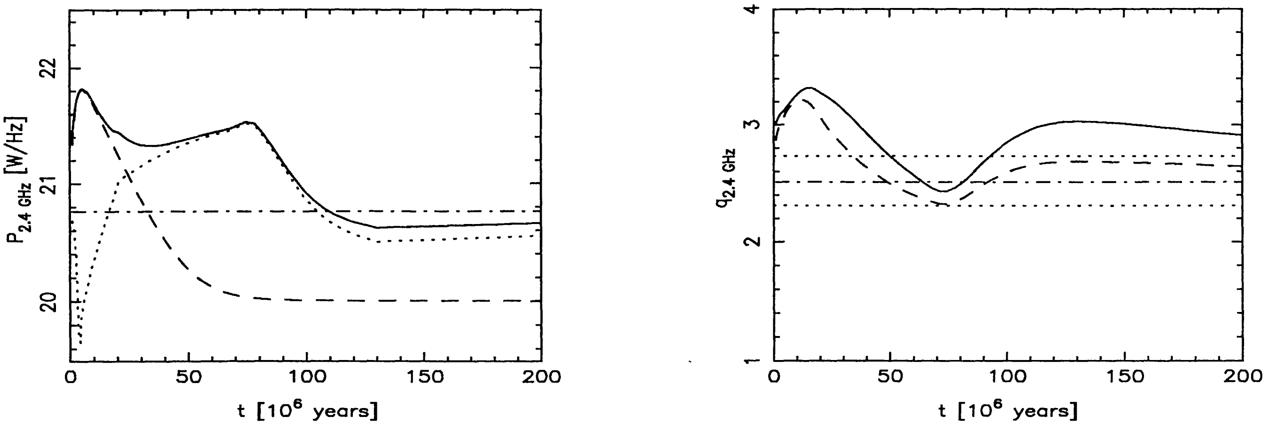

Fig. 1. For a starburst with $\tau_{\rm SB} = 10^7$ yr, $\tau_{\rm grow} = 0$, B=const it is shown: (Left side) The radio emission (full line) for $a = \Psi_0/\Psi_{\rm bg} = 100$, divided into thermal bremsstrahlung (dashed line) and synchrotron emission (dotted line). The dash-dotted line describes the steady state radio emission from the background galaxy. (Right side) The FIR/radio ratio at 2.4 GHz, $q_{2.4\rm GHz}(t)$, as a function of time for $a = 100$ (full line) and $a = 25$ (dashed line). The dash-dotted line represents the average $q_{2.4\rm GHz}$ of the comparison sample and the dotted lines show the 1 σ limits of this value.

2. THE DATA AND THE STARBURST MODEL

The samples were selected from the list of UGC galaxies which are surveyed with the Arecibo 300-m telescope at 2.4 GHz (Dressel & Condon 1978) and were covered by *IRAS*. In the *starburst sample* (133 objects) are those galaxies classified as peculiars, double, triple, or multiple systems, and galaxies identified by Markarian and collaborators as having ultraviolet excesses. Galaxies with active galactic nuclei (e.g., Seyfert galaxies) are not considered. The *control sample* (397 spirals) includes spiral galaxies at high Galactic latitude ($|b| > 40°$) and from the morphological types Sa through Sd, excluding Virgo cluster, Markarian, as well as Seyfert galaxies.

For the starburst sample, the mean of the FIR/radio ratio, $q_{2.4\rm GHz} = \log[(S_{\rm FIR}/3.75\ 10^{12})/S_\nu(2.4\rm GHz)]$, is 2.40 ± 0.03 with a statistical dispersion of $\sigma = 0.22$, while for the control sample it is 2.52 ± 0.02 ($\sigma = 0.21$). Therefore, although $q_{2.4\rm GHz}$ for the starburst sample is slightly lower than for the control sample, the difference is within the dispersion. Furthermore, we found no evidence for a dependence of $q_{2.4\rm GHz}$ on the starburst strength as indicated by the $f_{60\mu m}/f_{100\mu m}$ ratio or by the $L_{\rm FIR}/L_B$ and $P_{2.4\rm GHz}/L_B$ ratios.

In the starburst model the star formation is described as the sum of a background stellar population whose star formation rate (SFR) Ψ_{bg} is constant in time and a starburst population with a SFR $\Psi_{\rm SB}(t)$ changing on short time-scales in the following way:

$$\Psi_{\rm SB}(t) = \begin{cases} \Psi_0 \exp^{t/\tau_{\rm grow}} & \text{for } t < 0 \quad , \\ \Psi_0 \exp^{-t/\tau_{\rm SB}} & \text{for } t \geq 0 \quad , \end{cases}$$

where $\tau_{\rm grow}$ and $\tau_{\rm SB}$ are the time-scales of the increase and the decrease of the SFR. The ratio between the maximum SFR of the starburst population and the background population $a = \Psi_0/\Psi_{\rm SB}$ is a measure of the starburst strength. We assume a power-law Initial Mass Function $\Phi(m)dm = m^{-2.7}dm$.

The FIR luminosity has been calculated with the following assumptions: For massive, ionizing stars ($m > 20\,{\rm M}_\odot$) we assume that 60% of their luminosity is absorbed by the dust, 50% of which is reemitted in the FIR (40 – 120 μm) band. The radiation transfer of the non ionizing radiation of intermediate massive stars ($5\,{\rm M}_\odot < {\rm m} < 20\,{\rm M}_\odot$) and old stars ($1\,{\rm M}_\odot < {\rm m} < 5\,{\rm M}_\odot$) is approximated by an infinite parallel-slab geometry in which dust is homogeneously mixed with the stars. We simplify the picture further by assuming that for the intermediate massive stars the dust opacity in the UV (2000 Å) and for the old stars the dust opacity in the blue (4400 Å) is relevant. We assume that 30% of the nonionizing radiation that is absorbed by the dust is reemitted in the FIR band.

The radio emission consists of thermal bremsstrahlung and of synchrotron emission. The thermal radio emission is proportional to the total number of Lyman continuum photons which is calculated from the stellar spectrum. In order to calculate the synchrotron emission in a starburst a time-dependent equation has to be solved. Several processes are taken into account: We assume that the CR electrons are accelerated in shocks of SN remnants. Then they propagate into the galactic disk and halo losing their energy radiatively through inverse Compton and synchrotron losses. Since the radiation field in a starburst is very strong, the inverse Compton losses of the electrons are very high. This has the effect of shortening their radiative life-time, $\tau_{\rm loss}$, and therefore, of decreasing the temporal shift between the FIR and the synchrotron radiation. On the other hand, a high radiation field lowers the synchrotron emission itself, because the number density of electrons at a given energy is lowered. Therefore, during a starburst —if the magnetic field stays constant— the synchrotron emission is a sensitive function of the radiation field and therefore, of the starburst strength. In particular, it is very low during the phase of most active star-formation (see Fig. 1, left)

In Fig. 1 (right) the resulting FIR/radio ratio $q_{\rm 2.4GHz}(t)$ is shown for different values of the starburst strength a. The highest value of $q_{\rm 2.4GHz}$ and the largest discrepancy with respect to the data occurs during the first $\approx 2\,10^7$ yr of the starburst because the synchrotron emission is strongly suppressed due to inverse Compton losses caused by a high radiation field. At a later stage, ($t \approx 100 - 150$ Myr), $q_{\rm 2.4GHz}$ is again higher than the observed value because of the dust heating by low-mass stars ($m = 1 - 3\,{\rm M}_\odot$) causing a longer time-scale of the FIR emission with respect to the radio emission. This discrepancy can be removed by a longer starburst time-scale and a lower value of the starburst strength a.

3. THE MAGNETIC FIELD IN A STARBURST

The suppression of the synchrotron emission in the early starburst will be substantially diminished if the magnetic field increases rapidly. The time-scale of this increase has to be rather short ($\sim 10^7$ yr) because a large magnetic field strength is required already in an early stage of the starburst. If such an increase is taken into account, the data can be fitted well for $\tau_{\rm SB}, \tau_{\rm grow} \gtrsim 10^7$ yr.

The behaviour of the magnetic field in a starburst has not been well studied yet, but it seems plausible that the field increases. Ko & Parker (1989) proposed a model in which the increase of interstellar turbulence due to a high SFR activates a turbulent dynamo. Parker (1992) has argued that galactic dynamos can be driven by the pressure of CRs and the subsequent reconnection of azimuthal field lines to produce poloidal fields. Therefore during a burst of star formation, with the enhanced SN rate and the presumed associated increase in CR production, the galactic dynamo would be activated. However, the time-scale for the dynamo activity is rather long; it has been estimated between 10^8 (Ko & Parker) and $> 10^9$ yr (Field 1993). Therefore, a dynamo seems to be a too slow process to be relevant for the early starburst.

The increase of SN activity, stellar winds and associated interstellar turbulence during a starburst might enhance the magnetic field in a more direct way on shorter time-scales. A fluctuating dynamo (i.e., the stretching and twisting of magnetic field lines due to the interstellar turbulence) can create random magnetic field on a time scale of $\tau \sim l/v$ (l is the turbulent scale, v the turbulent velocity) (Parker 1979). This yields for Galactic values ($l = 100$ pc, $v = 10$ km s^{-1}) $\tau = 10^7$ yr. In a starburst the turbulent velocity is likely to be higher, thus τ could be even shorter. Alternative processes might be the compression by SN shocks of the ionized gas in which the magnetic field is frozen and a systematic dynamo effect due to a commencing galactic wind (i.e., the outward "combing" of the field by a mass outflow) as we may be observing in M82 or even at the centre of our Galaxy. The time-scales of these processes is given by the time-scale of stellar wind bubble evolution and SN activity.

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