# NASCENT STARBURSTS IN SYNCHROTRON-DEFICIENT GALAXIES

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**Abstract** We have identified a rare category of galaxies deviating from the universal infrared-radio correlation of star-forming galaxies in being significantly deficient in synchrotron radiation at 20 cm. The selected objects also have high dust temperatures, indicating intense radiation fields. From a detailed study of the prototype of this class, NGC 1377, the most likely scenario accounting for their properties is a starburst just breaking out in a host previously quiescent for at least 100 Myr. We have selected a statistical sample of candidate nascent starbursts from the cross-correlation of the IRAS Faint Source Catalog with the NVSS and FIRST VLA radio surveys, and discuss the first results obtained from a recent multi-wavelength VLA campaign.

## Introduction

The infrared-radio correlation of star-forming galaxies (Helou et al. 1985) suffers very few exceptions. At centimeter wavelengths, the radio continuum is dominated by synchrotron emission, from cosmic rays previously accelerated in supernova remnants, propagating in the interstellar magnetic field, and decaying in less than $10^8$ years (Condon 1992). The far-infrared continuum measures the peak of the dust emission, and is a fair tracer of the instantaneous star formation for starburst galaxies. The infrared-radio correlation can hold only if strong coupling mechanisms operate. The production rate of cosmic rays has to be roughly proportional to that of dust-heating photons (which is achieved for a fixed initial mass function), and in addition, starbursts seem to constantly adjust their magnetic field so that the ratio of magnetic energy density to radiation energy density remains constant (Lisenfeld et al. 1996). Yet, cosmic rays are released only about 4 Myr after the birth of their progenitors. This time delay implies that the relative amounts of infrared and radio emission are expected to vary significantly, and in

principle can be exploited to constrain the age of individual star forming regions. Galaxies, however, host young stellar populations which span an extended age range, and star formation, even in the form of bursts, goes on for significantly longer periods than 4 Myr ; radio continuum deficiency is thus exceedingly hard to achieve on large spatial scales. We term candidate nascent starbursts a class of galaxies selected in a specific way: they deviate upward from the average infrared to radio flux ratio by more than 3 times the standard deviation observed in star-forming galaxies ; and they have high far-infrared color temperatures, to ensure that dust is heated by intense radiation and that any cirrus component is negligible, so that the radio weakness cannot be explained by decayed star formation. We use
$\bar{q} = \log\ [1.26 \times (2.58\,F_{60} + F_{100})\,/\,3.75\,(\mathrm{THz})\ /\ S(20\,\mathrm{cm})] = 2.34 \pm 0.19$ (Roussel et al. 2003). In our interpretation, these galaxies host an intense star formation episode younger than a few Myr, and they have been previously quiescent for more than $\sim 100$ Myr (otherwise, the cosmic rays generated by previous star formation episodes would not have decayed completely). Such objects seem ideal to constrain the initial conditions, triggering mechanisms and early development of starbursts in galaxies, since they offer the setting to observe the onset of a burst unconfused by previous star formation episodes, a very rare occurrence.

## 1. The most extreme case: NGC 1377

NGC 1377 is the only member of the IRAS Bright Galaxy Sample undetected in the 20 cm continuum (Condon et al. 1990), and it deviates from the infrared-radio correlation by more than $8\sigma$. Its dust content is very hot, with $F_{60}/F_{100} = 1.2$ indicating a black-body temperature of 80 K, or a dust temperature of 54 K using a realistic emissivity law. NGC 1377 is a low-mass lenticular galaxy ($\mathrm{M}_* \sim 8 \times 10^9\,\mathrm{M}_\odot$), with $\mathrm{L}_{\mathrm{FIR}} = 4 \times 10^9\,\mathrm{L}_{\odot\ \mathrm{bol}}$. We review here briefly the essential aspects discussed by Roussel et al. (2003) ; readers are referred to this paper for more details and a discussion of alternative scenarios. We observed NGC 1377 at 3.6 and 6.3 cm, and obtained upper limits from which we conclude that the galaxy is not only devoid of synchrotron radiation, but also deficient in free-free emission. Using the star formation rate derived from the far-infrared, at least 70% of the expected ionizing photons are missing, which suggests that most of the energetic radiation is absorbed by dust. The reservoir of molecular gas is at least ten times more massive than what is required by the starburst hypothesis. It is very compact, possibly overcritical, and both the high infrared to CO(1-0) flux ratio (7 times the average for normal galaxies) and the low CO(2-1)/CO(1-0) brightness temperature ($0.53 \pm 0.14$) are similar to values encountered in starbursts. The only emission line detected in the near-infrared is that of $H_2$ (1-0) S(1) at 2.12 $\mu$m, and the limits obtained on the ratios of three $H_2$ transitions indicate slow shock excitation with $T \leq 1500$ K. From preliminary results of the SINGS survey (Kennicutt et al. 2003), the only bright emission line in the 10-35 $\mu$m range arises from $T \sim 200$ K $H_2$ gas, and no high-excitation lines are present. Finally, the ISOPHOT mid-infrared spectrum (Laureijs et al. 2000) is very unusual, containing a broad emission feature between 6 and 8.5 $\mu$m in place of aromatic bands universally found in metal-rich star-forming galaxies ; modelling of the infrared SED by a pure continuum with deep silicate absorption presents critical difficulties for the energy balance accounting for the moderate far-infrared power. Although it is often claimed that non-stellar activity is required to explain unusually hot and compact infrared sources, we have shown from energetics arguments that this is very unlikely for NGC 1377 (Roussel et al. 2003). The analogy between NGC 1377 and a scaled-up version of Becklin-Neugebauer objects, which represent the transition stage between protostars and ultracompact HII regions, may offer an interesting route to understand its many peculiarities.

## 2. A statistical sample of nascent starbursts

We have defined a new sample of synchrotron-deficient galaxies from the IRAS Faint Galaxy Sample and the NVSS and FIRST 20 cm VLA surveys, above a declination of $-35$ degrees. They were selected in infrared flux ($F_{60} > 0.7$ Jy), in infrared color ($F_{60}/F_{100} > 0.7$) and in infrared to radio flux ratio ($q \geq \bar{q} + 3\sigma_{\rm q}$). They are very rare objects, constituting only of the order of 1% of an infrared flux-limited sample, but make up a non-negligible fraction of systems brighter at 60 $\mu$m than at 100 $\mu$m ($\sim$ 16%). This sample contains an overwhelming majority of compact systems, many of which show morphological disturbances such as plumes or shells, or double nuclei. The galaxies which are classified are generally S(B)0-a, and of the HII or LINER types. These galaxies are not akin to dwarfs, which sometimes may be assimilated to a single giant HII region: they have near-infrared colors similar to those of massive galaxies, have high infrared to optical flux ratios, and compact reservoirs of CO gas, suggesting a normal metal content. All galaxies were observed by us with the VLA at 20 cm in the C configuration in order to obtain deeper maps. In addition, the galaxies with already robust limits at 20 cm were mapped at 3.5 and 6 cm, in order to constrain their radio emission mechanisms. Among this subsample, we found that 23 galaxies (59%) are intrinsically deficient in synchrotron emission. Their weakness at 20 cm is confirmed at shorter wavelengths. Sixteen other galaxies have spectral indices between 3.5 and 6 cm significantly steeper than between 6 and 20 cm, likely caused by high thermal opacity at 20 cm. If we correct for that effect by extrapolating the 3.5–6 cm spectral index, their deviation from the infrared-radio correlation is reduced, ranging between $0.6\sigma$ and $2.8\sigma$. They may represent a later evolutionary stage than the galaxies deviating from the correlation by more than $3\sigma$ at 6 cm. Six of the 23 galaxies genuinely poor in cosmic rays are still undetected at the 0.2–0.3 mJy level at 6 cm, and some may be considered faint analogs of NGC 1377. The radio spectrum of 11 other galaxies, steeper than $F_\nu \propto \nu^{-0.4}$, implies that the synchrotron component constitutes a significant fraction of their radio power, either the residue of an older star formation episode, or the product of a developing burst. Finally, 6 of the 23 truly synchrotron-deficient galaxies have 3.5–6 cm spectral indices flatter than $-0.4$. At least two seem completely dominated by thermal emission ; they are fairly luminous in the far-infrared ($2 \times 10^{10}\,\mathrm{L}_{\odot\ \mathrm{bol}}$ and $5 \times 10^{11}\,\mathrm{L}_{\odot\ \mathrm{bol}}$, respectively). They are both classified as LINERs, one is surrounded by faint shells and the other is a merging system (Figure 1). This preliminary analysis of the radio data underscores the diversity of the high infrared-to-radio ratio galaxies. The most useful information about their energy source, geometry and degree of evolution is expected to be brought by mid-infrared spectroscopy. A detailed description of the sample, data and analysis will be provided in a forthcoming paper.

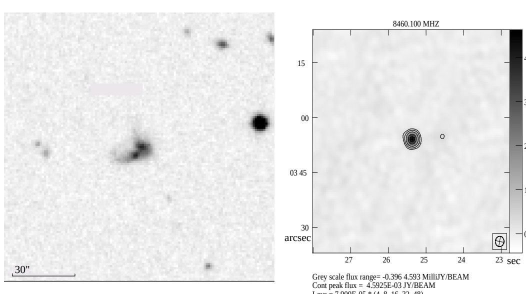


*Figure 1* The more luminous of the two systems whose spectral index between 3.5 and 6 cm is close to $-0.1$. To the left is an optical image from the Digitized Sky Survey ; to the right is the 3 cm VLA map.

## References

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