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NGC 1377: An Extragalactic Proto-Starburst

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Abstract. NGC 1377 is the archetype of a class of galaxies called nascent starbursts, selected by their very high infrared to radio continuum flux ratios and their high dust temperatures. This nearby galaxy is an ideal test case to refine the understanding of the mechanisms of the infrared-radio correlation of star-forming galaxies; to characterize the physical conditions of an embedded starburst at its very onset; and to gain a better knowledge of the activity of a class of ultraluminous galaxies sharing the main infrared-radio properties of NGC 1377. We present new data on NGC 1377 obtained as part of the *Spitzer* Infrared Nearby Galaxies Survey (SINGS) Legacy program and discuss briefly our interpretation of the combined optical, infrared and radio properties.

1. Introduction

NGC 1377 attracted our attention by being the only member of the *IRAS* Bright Galaxy Sample undetected in the radio continuum at 20 cm. It is also undetected at 6 and 3 cm, at the 1 mJy level. It is thus an extreme outlier to the infrared-radio correlation of star-forming galaxies described by Helou et al. (1985). The radio continuum is deficient by a factor > 37, corresponding to a significance level $> 8\sigma$. Since the infrared-radio correlation is quasi-universal and tight (except for Seyfert galaxies which may be overluminous in the radio, and dwarf galaxies which show a much larger dispersion than massive galaxies), NGC 1377 and its analogs possibly offer a new route to confirm or refine the models accounting for the infrared-radio correlation, particularly in what regards the amplification of magnetic fields in starbursts.

The centimeter radio continuum is usually dominated by synchrotron emission, from cosmic ray electrons previously accelerated in type-II supernova remnants, propagating in the interstellar magnetic field, and decaying in less than 10^8 years (Condon 1992). The fractional contribution of thermal electrons to centimeter fluxes is small in normal galaxies. Models successfully describing the infrared-radio correlation (e.g. Beck & Golla 1988; Helou & Bicay 1993) invoke proportional production rates of cosmic rays and dust-heating photons (which is achieved for a constant initial mass function) and a strong coupling between the magnetic field intensity and either the gas density or the star formation rate. A solid empirical constraint on the latter point comes from the fact that starburst galaxies with very intense radiation fields obey the general correlation, which implies that inverse Compton losses are balanced by synchrotron losses,

hence that the magnetic field has been amplified quickly enough to realize this adjustment (Condon et al. 1991).

NGC 1377 is also characterized by a hot dust content ($F_{60}/F_{100} \sim 1.2$), heated by an intense radiation field most likely produced by a compact starburst. Non-stellar activity is not plausible, for several reasons detailed below. The absence of synchrotron emission in NGC 1377 is most naturally interpreted as an absence of cosmic ray electrons, which poses stringent constraints on the evolutionary stage of the starburst. In this case, the starburst must be younger than the lifetime of massive stars evolving into type-II supernovæ ($< 5\,\mathrm{Myr}$), and previous major star formation episodes must be older than the timescale for relativistic electrons to decay ($> 100\,\mathrm{Myr}$). It is impossible to account for the absence of cosmic rays by an initial mass function deficient in high-mass stars, since this would imply an absurd value for the mass of the starburst (Roussel et al. 2003).

An interesting alternative, and the only one that seems viable, is a more mature starburst in which cosmic ray electrons undergo severe inverse Compton losses effected by the intense infrared radiation field, and decay so quickly that they disappear before the next supernova explosion. Serious difficulties however arise from the fact that the starburst would have to remain completely embedded (see below), despite the disruptive effects of stellar winds and supernova shock waves, and thus confined by an abnormally high pressure for a long period. Until new elements allow us to assess the likelihood of this scenario, we favor the nascent starburst hypothesis as the most natural one.

We present here some new data from the *Spitzer* SINGS Legacy program on NGC 1377, and briefly discuss the implications. The reader is referred to Roussel et al. (2003, 2006) for more details and more results.

2. Dust and Gas in a Nascent Starburst

Figure 1 shows the infrared spectral energy distribution of NGC 1377, obtained with IRS spectroscopy between 5 and 36 μm and IRAC, ISOCAM, MIPS and IRAS broadband photometry between 3.6 and 160 μm. High-resolution IRS spectroscopy has also been analysed. The main results can be summarized as follows:

- The infrared source is compact ($< 100\,\mathrm{pc}$ in diameter), centered on the nucleus. The total infrared luminosity is $\sim 1.1 \times 10^{10}\,\mathrm{L}_\odot$, corresponding to a starburst mass of $\sim 16 \times 10^6\,\mathrm{M}_\odot$ for a lower-mass cutoff of $0.1\,\mathrm{M}_\odot$, similar to the most massive super star clusters known (e.g. Gilbert et al. 2000).
- The dust emission is dominated by a hot continuum that is strongly self-absorbed, with very deep absorption bands from amorphous silicates at 10 and 18 μm. Radiative transfer modelling with DUSTY (Nenkova et al. 2000), in the hypothesis of a single and spherically-symmetric source, indicates an optical depth $\tau_\mathrm{V} \geq 75$ and $\tau(10\,\mu\mathrm{m}) \sim 20$.
- The only tracer of HII regions that was detected is a very faint [NeII] line at 12.8 μm. The upper limit on the free-free emission at 3 cm implies that more than 85% of the ionizing photons are absorbed by dust. Because of

this effect combined with high extinction in the mid-infrared, the [NeII] line probes $< 1\%$ of the ionizing radiation.

– The near-infrared and mid-infrared line spectrum is dominated by molecular hydrogen lines at temperatures between 350 K and < 1500 K. Given the uncertainties in current models of photodissociation regions, a dominance from these in H_2 heating is not ruled out, but most of the warm molecular gas is arguably heated by shocks.

The starburst in NGC 1377 appears to be so young that most massive stars are still embedded in molecular material, and have at most created ultracompact HII regions, where nebular emission is quelled. Optical imaging reveals a peculiar morphological distortion suggesting that a merger or accretion event could be the trigger of the starburst. Optical spectroscopy provides evidence for shocks in the foreground of the region of activity. Although NGC 1377 might be classified as an AGN or LINER based on optical line ratios (e.g. $F([\mathrm{NII}])/F(\mathrm{H}\alpha) > 1$), we emphasize that since the optical emission does not probe the nuclear regions, such a classification is meaningless for NGC 1377.

Non-stellar activity is very unlikely for the following reasons: 1) Seyfert galaxies either follow the infrared-radio correlation or have a radio excess ; while the deficit of synchrotron emission can be understood easily in terms of a nascent starburst, it cannot in terms of Seyfert activity. 2) For the maximum black hole mass allowed by usual scaling relations, even Eddington power with 100% dust heating efficiency would not account entirely for the observed infrared power. 3) The upper limit on the [NeIII] to [NeII] line ratio, not significantly affected by differential extinction or by collisional de-excitation, indicates low excitation, which is consistent with the dominance of ultracompact HII regions, but not with the hard radiation from a Seyfert nucleus.

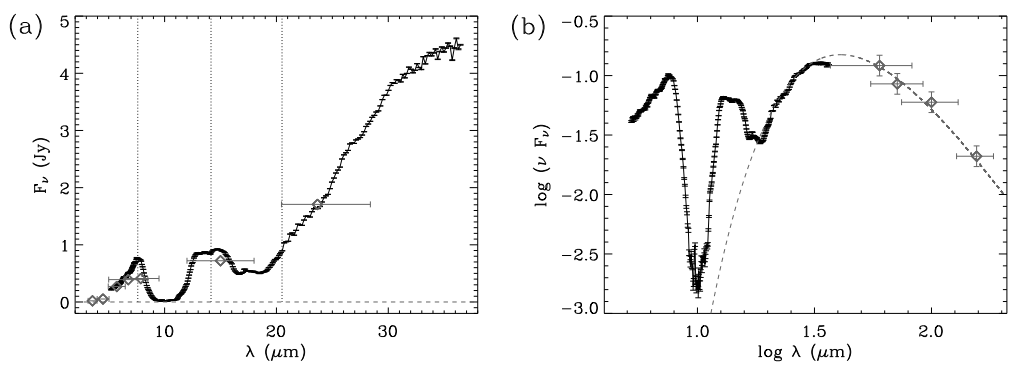

Figure 1. Spectral energy distribution of NGC 1377 between **(a)** 3 and 40 μm, in flux density units ; **(b)** 5 and 160 μm, in power units and logarithmic scale. Notice the very deep absorption bands from amorphous silicates at 10 and 18 μm. Broadband imaging photometry is overplotted as grey diamond symbols with horizontal error bars representing the filter widths. In **(a)**, different spectral orders are separated by vertical lines. In **(b)**, the spectrum from a 90 K blackbody is overplotted as a dashed line.

3. Relevance for Infrared Surveys

Figure 2 compares the mid-infrared spectra of NGC 1377 and IRAS 08572+3915, the galaxy with the highest apparent optical depth in the sample of deeply obscured ultraluminous galaxies of Spoon et al. (2006). The far-infrared (40–120 μm) luminosity of IRAS 08572+3915 is $\sim 5 \times 10^{11}\,L_{\odot}$, about 100 times the far-infrared luminosity of NGC 1377, and also deviates from the infrared-radio correlation by having a significant infrared excess. The striking similarity of the infrared-radio properties of these two objects suggests that the physical processes at the origin of the observed activity are the same.

Nascent starbursts are rare objects in the local universe (radio-deficient galaxies represent $\sim 16\%$ of systems with $F_{60} > F_{100}$, and only of the order of 1% of a flux-limited infrared sample). Their rarity is consistent with the brevity of their evolutionary phase and with the timescales of star formation. However, they may occur more frequently at earlier epochs, as suggested by the existence of a large population of galaxies with hot dust at redshifts $z \sim 2$ (Chapman et al. 2004). Figure 2 (right panel) demonstrates that nascent starbursts could have a significant effect on the interpretation of deep survey counts.

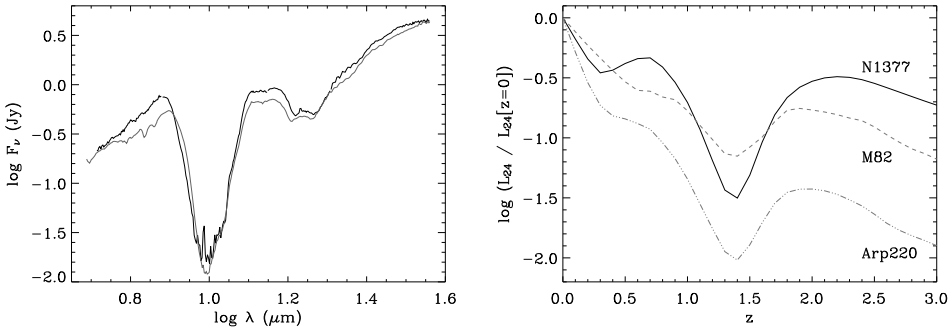

Figure 2. **Left:** Rest-frame mid-infrared spectra of NGC 1377 (Roussel et al. 2006, in black) and IRAS 08572+3915 (Spoon et al. 2006, normalized at 36 μm, in grey). **Right:** Evolution of the luminosity in the 24 μm MIPS filter as a function of redshift, for the spectral energy distributions of NGC 1377 and the popular starburst templates M 82 and Arp 220.

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