Extragalactic Embedded Clusters: Exploring Star Formation

Infrared techniques today allow us to explore the first ages of star formation in starburst galaxies: young massive clusters buried in a thick dusty cocoon reveal their nature through infrared imaging and spectroscopy.

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How star formation takes place in galaxies is a topic which has been studied extensively over the past decades: in particular, the discovery of starburst galaxies in the early 80's (Weedman et al. 1981) drew attention to the fact that, under certain conditions, the star formation rate could be extremely high and very different from what is currently observed in our Galaxy or in the Magellanic Clouds. Of course, the diversity in star forming conditions was already known from the mere existence in galaxies of at least two populations of star clusters, the open clusters and the globular clusters. Yet, the starburst phenomenon was revealing a new side of star formation and its occurrence on unprecedented scales, opening insights into the history of star formation over cosmic times. Starbursts are mostly found in the central regions of spiral galaxies still rich in gas and dust, and are the site of ~25% of the high-mass star formation. One hundred solar masses of stars per year can be formed in a starburst galaxy, while this rate is only one solar mass per year in the disc of the Milky Way. Hence, extragalactic starbursts constitute a natural laboratory for testing our ideas about star formation, about the evolution of massive stars and the physics of the interstellar medium; they might be as well a testimony of processes which were certainly of prime importance in the early ages of galaxies.

Deep imaging surveys in the infrared and submillimetre (using ISO, SCUBA and/or COBE) have demonstrated that half of the energy of the extragalactic background at these wavelengths is emitted by extremely red starburst galaxies (Madau 1999). Consequently, studying their local analogues, the nearby dusty starburst galaxies, brings clues about the predominant mode of star formation at remote epochs and contributes to our understanding of the evolution with time of the initial mass function, the star formation rate and the chemical enrichment of galaxies.

Thanks to observations at increased spatial resolution, the star forming regions in starburst galaxies have been resolved into entities which are sometimes called super star clusters (SSCs) or young massive clusters (YMCs). These clusters have sizes from 0.5 to 20pc and weigh from 10^5 to 10^6 solar masses. Starburst galaxies like NGC253, M82 or NGC1808 contain hundreds of such clusters, while in the exceptional case of young mergers like the Antennae galaxies their numbers can surpass one thousand.

As of today, several questions remain matters of hot debate, among them:

- What are the specific physical conditions which lead to the formation of YMCs in starbursts, and in particular, what is the role –if any– of the active galactic nucleus (AGN) often observed at the centre of actively star forming galaxies? Is the long-standing claim of an AGN-starburst association (at face-value still unproven) a favourable factor for the formation of massive star clusters? Is this factor related to the infall of material toward the AGN?
- What is the fraction of stars which were indeed born in YMCs and is there a connection between the YMCs observed in starbursts and the evolved globular clusters in the halos of galaxies?

The sizes, masses and stellar velocity dispersions of YMCs are comparable to those of globular clusters. Conversely, the ages of these two classes of objects differ by a factor 1000: while the oldest globular clusters are nearly as old as the universe (~13 Gyr), young massive clusters are only a few to 100 Myr old. Numerical simulations as well as analysis of the observed cluster mass distribution in the two classes of objects suggest that only the most massive clusters remain bound through a Hubble time, while the least massive ones are dispersed, providing a potential reservoir for field stars (Fall & Zang 2001). Under such a scenario, the YMCs would be the progenitors of stars currently gravitationally bound in globular clusters or stars in the field, depending on their initial mass. Whether the observed stellar mass function in young massive clusters is consistent, after the stellar population has evolved, with that observed in globular clusters, remains an open and controversial point (Elmegreen 1999).

One of the limitations in the study of star formation processes within starbursts arises from the fact that most analyses of YMCs have focused on their optical properties. Yet, there is strong evidence that some young massive clusters are almost completely obscured by dust, and hence invisible in the optical. In such cases, only infrared (IR) or radio studies can reveal their presence. The first outstanding example of such embedded YMCs is to be found in the Antennae galaxies, where Mirabel et al. (1998), comparing mid-infrared (MIR) ISO images with HST optical images, discovered a powerful star forming region which was detectable only on the MIR images. Just a few other examples of such intense –and hidden– star forming activity are known to date. However, the near future –with MIR instruments such as VISIR on the VLT– promises many more discoveries and a better understanding of the starburst phenomenon and of its implications on the evolution of galaxies.

We present in the following how new populations of embedded young massive clusters were uncovered in NGC1365 and NGC1808, and illustrate the potentialities of NIR spectroscopy for the study of these objects.

Associated MIR/radio sources: embedded star clusters?

Let us now focus on NGC1365 and NGC1808. These two galaxies have long been known to display enhanced star formation in their central region (radius between 500pc and 1kpc) and to host an AGN. In both cases, HST has resolved out a population of bright (un-embedded), compact and young star clusters, in the star bursting central region.

In parallel, high-angular resolution radio

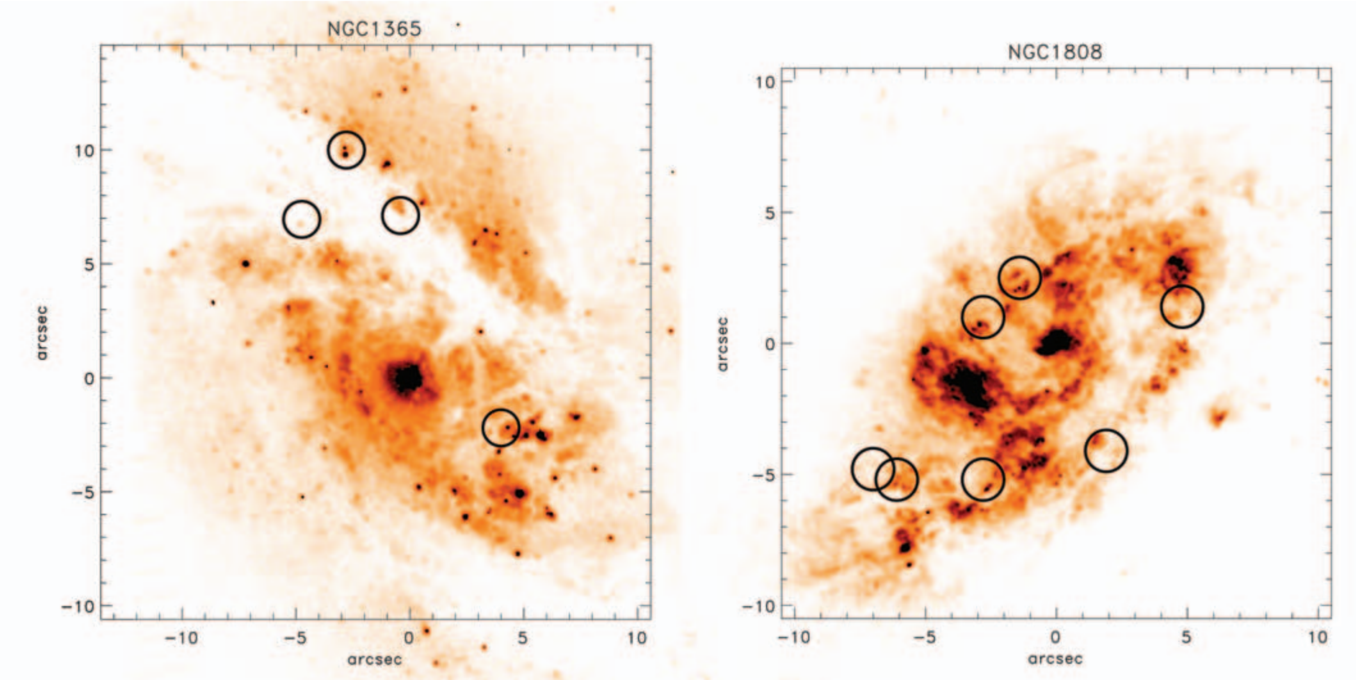

Figure1: Archive HST images of the starburst regions of NGC1365 (F814W) and NGC1808 (F658N). These galaxies are respectively located at 18.6Mpc and 10.9Mpc, translating into linear scales of 90 pc/″ and 50 pc/″. North is up and East is left. The circles show the locations of the brightest compact centimetre radio sources (Forbes & Norris 1998 and Collison et al. 1994). The lack of correlation between the structures seen in the optical and the radio sources is striking.

maps have been obtained at centimetre wavelengths and unveiled the presence of a population of circumnuclear bright radio sources. Interestingly, the positions of these sources do not match the positions of the brightest optical knots detected with HST. Figure 1 displays archive optical images obtained with HST/WFPC2, on top of which circles mark the positions of the brightest observed centimetre sources. The observed centimetre spectral index of the sources indicates the presence of non-thermal processes: as no obvious optical counterpart to most of the radio sources could be found, they were proposed to be individual radio supernovae. Indeed, radio supernovae are intense synchrotron sources that appear and disappear within periods of months to years after Type II or Type Ib supernovae events. However, because of the short lifetime of radio supernovae, the fact that several of the centimetre sources could be observed simultaneously made this interpretation rather unlikely, and the nature of these sources remained somewhat mysterious.

Recently, we have obtained high angular resolution images with 3.6m/TIMMI2 at La Silla, and discovered the bright MIR counterparts of these radio sources (Galliano et al. 2004). Hence, the whole picture gets clearer: they can now be interpreted as the signature of young embedded massive clusters. Rough estimates of their ages and masses corroborate this interpretation: from their centimetre and MIR fluxes, and from their spectral indexes, these embedded clusters are found to have masses on the order of 10^6 solar masses, and ages of a few million years. The observed non-thermal component at centimetre wavelengths can result from a high rate of supernovae, coinciding with the evolutionary stage of the star cluster population when the most massive stars undergo collapse (one every few thousand years). Still, the MIR observations only provide indirect evidence of the presence of massive young star clusters associated with the radio and MIR sources. Some more direct evidence ought to be found, such as signatures of the strong ultraviolet radiation field expected from the massive young stars.

Searching for HII regions through the dust

In this section, we present new data obtained with VLT/ISAAC, which give direct evidence for the presence of massive young star clusters associated with the compact radio/MIR sources in the circumnuclear regions of NGC1365 and NGC1808.

At the early evolutionary stages of a star cluster, very massive stars are still present, and until an age of about 6 Myr, the emission is dominated by nebular lines and continuum from the ionised regions (called HII regions) surrounding the massive hot stars, rather than by stellar photospheric emission. Hence, a direct proof that the radio/MIR sources are indeed young massive clusters is the detection of the nebular emission excited by the ionising photons emitted by the massive stars. There were good reasons to search for such a proof in the NIR: the effects of extinction are minimised and a wealth of nebular lines are present in this wavelength range. Nebular lines from embedded star clusters had so far only been detected in two sources, namely the Antennae Galaxy and NGC5253, respectively by Gilbert et al. (2000) and Turner et al. (2003) with NIRSPEC on the Keck telescope.

Using ISAAC/VLT, we have obtained *K* (2.2µm) and *L* (3.5µm) images of NGC1365 and NGC1808, as well as low resolution spectra of the brightest radio/MIR sources. The results are displayed in Fig. 2. Composite colour images (Red=10µm, Green=3.5µm and Blue=2.2µm) are shown together with the *K*-band (1.9-2.4µm) and *L*-band (3.2–4.2µm) spectra of the reddest sources. These coincide spatially with the intense radio centimetre sources mentioned above. The nebular emission from the HII regions surrounding the most massive stars still present in these clusters is clearly detected through Hydrogen recombination

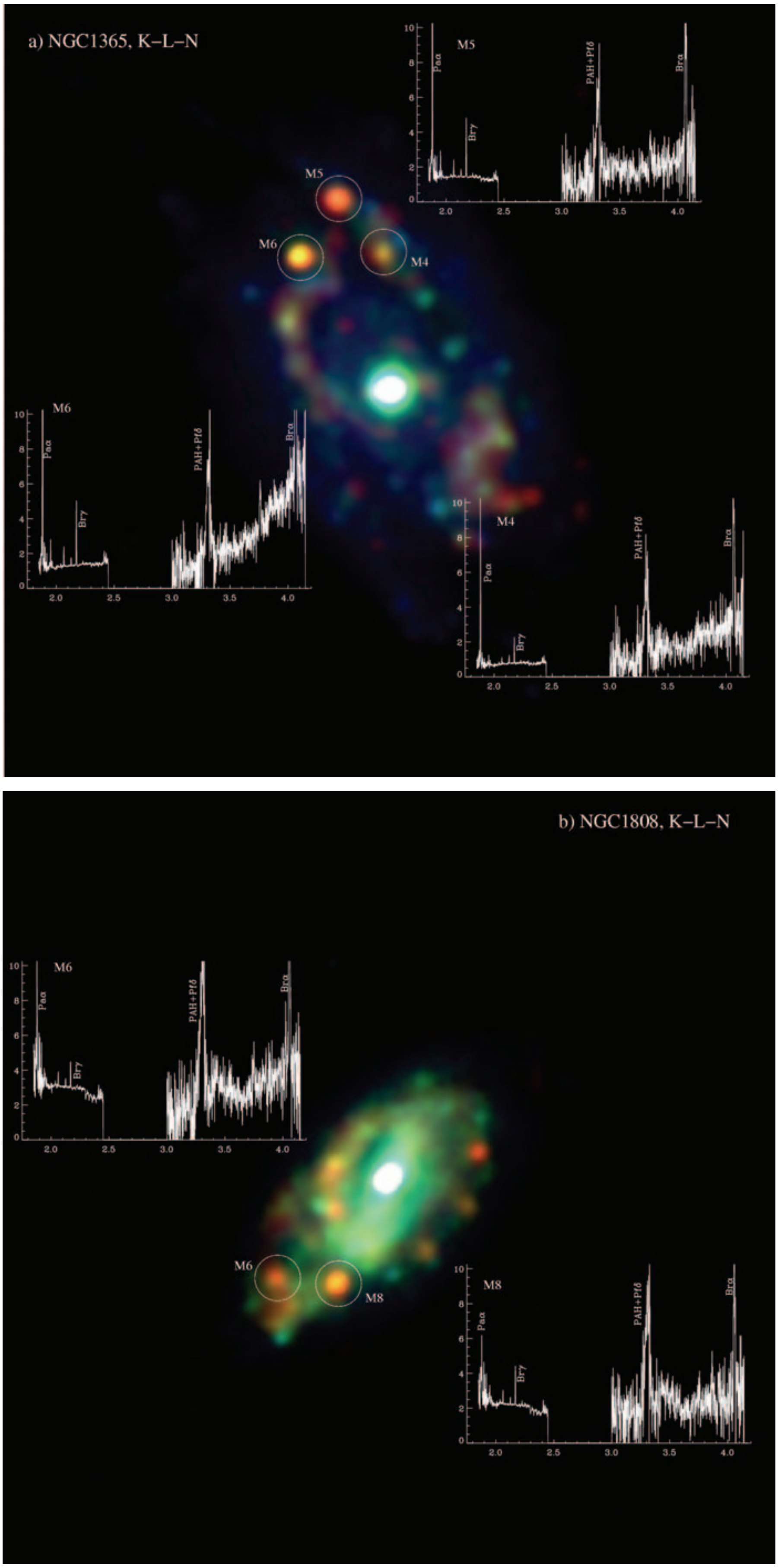

Figure2: Composite colour images of the central region of NGC1365 (a) and NGC1808 (b). Blue corresponds to the *K*-Band (2.2μm), green to the *L*-band (3.5μm) and red to the *N*-band (10μm). The dimensions of the image are 40″ × 40″ (3.6kpc × 3.6kpc for NGC1365 and 2.1kpc × 2.1kpc for NGC1808). North is up, East is left. The central bright source on each image is the AGN. The reddest sources in the circum-AGN environment identify the deeply embedded young massive star clusters, found in spatial coincidence with the observed intense centimetre radio sources. The nature of these sources is directly revealed by the *K*- and *L*-band spectra, given for the circled sources. The X-axis of each plot shows the wavelength in μm and the Y-axis the flux density in mJy. Between approximately 2.5μm and 3μm, the opacity of the atmosphere does not allow to record data from the ground. Nebular lines arising from the ionised regions surrounding the massive stars are detected (Paα, Brδ, Brγ, Pfγ and Brα). Moreover, the spectra show H_2 and PAH emission excited in the photo-dissociation regions surrounding the clusters. For clarity, only the most prominent lines were labelled. The observations were made with VLT/ISAAC in the *K*- and *L*-bands, and with TIMMI2 in the *N*-band.

lines (by increasing wavelength: Paα, Brδ, Brγ, Pfγ and Brα). Several H_2 lines are detected in the *K*-band spectrum and a clear signature of PAH emission is seen at 3.3μm. These molecular lines trace the emission from photo-dissociation regions (PDR) surrounding the clusters and are excited by far UV radiation from the massive stars. The analysis of these observations will be presented in a forthcoming paper.

The results presented above illustrate the potential of IR imaging and spectroscopy for the study and understanding of star cluster formation processes.

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