Abstract.

Near infrared adaptive optics observations are crucial to be able to interpret kinematic and dynamical data and study star formation properties within the often extremely dusty interacting luminous IR galaxies (LIRGs). NIR AO data are also needed to find supernovae in their bright and dusty central regions and to fully characterize the young stellar clusters found in these kinds of systems. We have used AO in the $K$-band to survey a sample of LIRGs at 0.1 arcsec (30 to 100 pc) resolution. The data are merged with SALT and AAT spectroscopic follow-up and HST and Spitzer archival imaging. The first AO detected SNe are reported as well as details of the first studied LIRGs. One LIRG showed an unexpected third component in the interaction, which moreover turned out to host the most active star formation. Another target showed evidence in the NIR of a very rare case of leading spiral arms, rotating in the same direction as the arms open.

1 Introduction

In the local Universe luminous and ultra-luminous IR galaxies are a minority (LIRGs have $L_{IR} = 10^{11} - 10^{12} L_\odot$ and ULIRGs $L_{IR} > 10^{12} L_\odot$; see Sanders & Mirabel 1996, for a review). They are very dusty objects with a mixture of on-going AGN activity and strong star formation (SF), and hence must also be locations of frequent core-collapse supernovae (CCSNe). They are mostly interacting and merging gas-rich spirals. At higher redshifts they start to dominate the universal SF, LIRGs and ULIRGs at $z \sim 1$ and $z \sim 2$, respectively, (Le Floc'h et al. 2003). It was proposed early on that they may be a link in an evolutionary sequence between spiral galaxies and ellipticals, via mergers, obscured AGN and QSOs. With this connection to early galaxy formation and evolution and to key galaxy transformational processes, the local (U)LIRG population can be thought of as a laboratory to study in detail processes such as SF triggering and starburst vs. AGN interplay and black hole growth.

The picture has become more complicated however. It is not clear that higher redshift (U)LIRGs have the same characteristics, apart from their high bolometric luminosity, as the ones at lower redshifts. Recent studies have shown that a large fraction of LIRGs at $z \sim 0.6$ are quite regular disks without evidence for strong interactions (e.g. Melbourne et al. 2008) and that higher redshift ULIRGs have much colder dust temperatures than local examples (e.g.
Symeonidis et al. (2009), temperatures that are closer to local cirrus dominated quiescent spirals.

Most of the studies and surveys of IR-luminous galaxies over the past two decades have concentrated on the most luminous and striking population, the ULIRGs. With the realization that the higher redshift ULIRGs actually have many physical characteristics (dust properties, SEDs, morphologies) more similar to local less-luminous IR galaxies closer to $L_{IR} \sim 10^{11}L_\odot$, larger detailed surveys of this latter class are well motivated.

2 Observations

What has been missing from local LIRG, as opposed to ULIRG, surveys are very high spatial resolution imaging data in the NIR to match optical HST data already in the archives. We have undertaken a $K$-band adaptive optics survey of local LIRGs with $\sim 0.1^\prime$ resolution. Our pilot study was a 2-epoch survey with VLT/NACO and natural guide stars of a sample of a dozen southern LIRGs at $< 200$ Mpc. We now have an on-going multi-epoch survey with Gemini ALTAIR/NIRI using laser guide stars. This sample consists of 8 LIRGs at $< 120$ Mpc. The combined multi-epoch $K$-band images reach down to $K \sim 22$ mag. The observations are aimed at both identifying CCSNe in the highly obscured central regions of LIRGs and to study the LIRGs themselves in conjunction with spectroscopic follow-up observations and archival optical HST and mid-IR Spitzer data. While the main statistical results are awaiting the completion of the Gemini survey and more follow-up spectroscopy, we have already detected new CCSNe in both surveys, and followed up two of the LIRGs from the VLT survey in detail. These will be discussed below.

3 The Bird: a triple merger

NACO imaging of IRAS 19115-2124 was combined with Southern African Large Telescope (SALT; O’Donoghue et al. 2006) observations and HST/ACS and Spitzer archival data for a detailed case study (Väisänen et al. 2008a) – we dubbed the system the Bird galaxy because of the obvious resemblance (Fig. 1). The NIR imaging pinpointed the mass distribution in the system, which we then proceeded to study with long-slit spectroscopy ($R \approx 2800$) in the range $\lambda = 5800$ to 7200 Å at various slit position angles. We determined line ratios, kinematics, velocity curves and dispersions, and mass estimates based on both spectral data and $K$-band M/L estimates. Three independent kinematical components were found rather than the typical two interacting spirals in LIRGs. The “Heart” and “Body” components are the more massive ones, both $\sim 5 \times 10^{10}M_\odot$; the first is a spiral disk galaxy and the latter has a surface brightness profile intermediate between spirals and ellipticals. The “Head” is an irregular with $< 1/4$ of the mass of the main components. It should be stressed that the Head component can only be identified from the NIR imaging and the Body is nearly completely obscured in the optical. The tidal tails, the Wings of the Bird, extend to 20 kpc.

A strong NaD doublet absorption feature in the SALT spectrum shows blue-shifted components interpreted as cool gas outflowing from the system, while blueshifted emission line ratios show signs of shock-heating.
A SFR of 190 M\(_\odot\) yr\(^{-1}\) was derived from the optical-FIR SED. Interestingly, the smallest component, the Head, is the one forming stars most rapidly, accounting for approximately 2/3 of the 24 \(\mu\)m flux of the whole system (Fig. 1). Given its high offset velocity of \(\sim 400\) km/s with respect to the systemic velocity, we believe the Head must be on its first encounter with the other two galaxy nuclei. The more massive nuclei have bar structures evident, which are thought to efficiently funnel gas to feed central starbursts. Interesting questions remaining to be answered include why the dominant SF is not at the central location, and when and why was the current burst of SF in the Head triggered.

### 4 Leading arms?

IRAS 18293-3413 has been followed up with NIR spectroscopy at the AAT and with archival data ([Väisänen et al. 2008b](#)). This system also was found to have a minor component, this time of less than 1/15 relative mass and with a high relative velocity of \(\sim 500\) km/s. The striking surprise here were the spiral arms of the main component, which are visible only in the \(K\)-band images. Judging the orientation of the galaxy in space from extinction arguments (Fig. 2 right) and combining this with the direction of rotation from spectra, we arrive at the conclusion that the spiral arms move in the same direction that they open up, i.e. IRAS 18293-3413 is a leading arm spiral.

If the result holds up with more detailed data this would be one of only 2 or 3 convincing candidates of leading arm spirals ([Byrd et al. 1993](#); [Grouchy et al. 2008](#), and references therein). This kind of galaxy is not forbidden by theory, and in fact simulations have shown that some retrograde encounters should produce them ([Thomasson et al. 1989](#)) and that they would have implications for e.g. the dark matter halo mass of spirals.
Figure 2. Left: IRAS 18293-3413 NACO $K$-band image. AAT NIR spectroscopy was taken along the major axis (SE to NW) and the rotation curve is shown at top right as curves for line emitting gas and as circles for CO-band absorption. Bottom right: The black curve is a surface profile over the $K$-band bulge along the minor axis. The red thinner line is the NE-side profile mirrored on the SW side, showing that the latter is more affected by extinction, suggesting it is the nearer side to the observer resulting in the leading arm configuration. See Väisänen et al. (2008b) for discussion.

Figure 3. IRAS 17138-1017 observed with Gemini AO in the NIR bands at left, and an archival HST/NICMOS image in the middle. SN2008cs is seen in the lower part of the galaxy in the Gemini image and a “historical” SN2004iq left of the nuclear regions in the NICMOS image. Right: VLA contour overlay on our subtracted $K$-band NACO data of IRAS 18293-3413. SN2004ip is visible both in the NIR and radio wavelengths.
Searching for obscured core-collapse Supernovae

The large SFRs in LIRGs are expected to result in CCSNe at rates a couple of orders of magnitude higher than in ordinary field galaxies. This SN population is missed by optical ground based surveys because most of them are expected to occur in the bright nuclear regions, and are also likely to be heavily dust-obscured. NIR AO observations greatly increase their detectability with regard to both extinction and spatial resolution. The detected CCSNe can be used as a direct and independent way to probe the SFR in galaxies both locally and in the distant Universe (e.g. Dahlen et al. 2004).

Our first SN discovery SN2004ip (Mattila et al. 2007) from the VLT/NACO sample was also the first ever AO-assisted SN discovered. Subsequent radio observations confirmed its CCSN nature (Pérez-Torres et al. 2007; Fig. 3 right). SN2004ip at a projected distance of 1.4", or 500 pc, from the nucleus of IRAS 18293-3413, is among the closest SNe detected (in IR) to a LIRG nucleus.

Observations with Gemini ALTAIR/NIRI of IRAS 17138-1017 have so far produced two SN discoveries (Fig. 3, left & centre; Kankare et al. 2008a). SN2008cs is located at 4.2", or 1.5kpc, projected distance from the nucleus. We obtained follow-up observations in \( JHK \) bands which are consistent with a core-collapse event suffering from a very high host galaxy extinction of \( A_V \approx 16 \) mag, the highest yet measured for any SN. The CCSN nature of SN 2008cs was also confirmed by radio observations. The “historical” SN 2004iq (Kankare et al. 2008b) detected in the HST images is located 660 pc from the nucleus and suffers from a lower extinction.

Super Stellar Cluster candidates

All the LIRGs in our sample have many obvious point sources embedded in the galaxies, likely young (super) stellar clusters (SSCs), which are expected to frequent strongly star forming galaxies. As seen in Fig. 2, the spiral arms of IRAS 18293-3413 are ubiquitously traced by SSC candidates in the NIR. Systems with stronger SFRs should have more SSCs, and it is more probable to find brighter and more massive SSCs in stronger starbursts (Larsen 2002). Indeed, the brightest SSC candidates in the Bird and IRAS 18293-3413 galaxies follow very well the SFR vs. brightest-\( M_V \)-cluster relation of Bastian (2008).

SSC characteristics and their luminosity functions have not been studied very much in the NIR yet. Our NIR AO-observations provide an excellent dataset to characterize the NIR SSC population for comparison with the optical studies, to see whether LFs and dependencies of global galaxy parameters are similar. As shown in Fig. 4 there are many SSCs seen in \( K \)-band not seen at ACS \( I \)-band, and also SSCs at \( I \)-band which are weak or not detected in the NIR, suggesting both heavy dust obscuration and age differences. A full comparison of the \( K \)-band SSCs in our dozen or so LIRGs with optical SSC data and also with MIR detected deeply embedded clusters should be intriguing.
Figure 4. A region of 4.5"x2" just North-West of the nucleus of IRAS 18293-3413 showing many SSC candidates. Our VLT/NACO data is on the left and HST/ACS I-data on the right.

7 Summary

It is absolutely critical to perform AO-assisted NIR observations to detect what is really going on within the very dusty and often chaotic (U)LIRGs. Otherwise whole progenitor nuclei in the interacting systems may be missed, and histories of the interactions and star formation might be misinterpreted. The data are also crucial in detecting a population of CCSNe in high SFR galaxies.

Two LIRG case studies were presented from an ongoing survey. SNe were detected, as expected, and the new parameter space of resolution and wavelength provided surprises in the form of “extra” nuclei and unusual spiral patterns. Follow-up studies of other LIRGs and their SSCs are continuing.

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