Highlights of Spanish Astrophysics VII, Proceedings of the X Scientific Meeting of the Spanish Astronomical Society held on July 9 - 13, 2012, in Valencia, Spain. J. C. Guirado, L. M. Lara, V. Quilis, and J. Gorgas (eds.)

The radial distribution of supernovae in nuclear starbursts

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Abstract

Galaxy-galaxy interactions are expected to be responsible for triggering massive star formation and possibly accretion onto a supermassive black hole, by providing large amounts of dense molecular gas down to the central kiloparsec region. Several scenarios to drive the gas further down to the central ~100 pc, have been proposed, including the formation of a nuclear disk around the black hole, where massive stars would produce supernovae. Here, we probe the radial distribution of supernovae and supernova remnants in the nuclear regions of the starburst galaxies M82, Arp 299-A, and Arp 220, by using high-angular resolution ($\lesssim 0.''1$) radio observations. We derived scale-length values for the putative nuclear disks, which range from ~20–30 pc for Arp 299-A and Arp 220, up to ~140 pc for M82. The radial distribution of SNe for the nuclear disks in Arp 299-A and Arp 220 is also consistent with a power-law surface density profile of exponent $\gamma = 1$, as expected from detailed hydrodynamical simulations of nuclear disks. This study is detailed in [8].

1 Introduction

The activity in the central regions of luminous and ultra-luminous infrared galaxies (LIRGs, $10^{11} L_\odot \leq L_{\rm IR} < 10^{12} L_\odot$, and ULIRGs, $L_{\rm IR} \geq 10^{12} L_\odot$, respectively) is powered by either accretion onto a supermassive black hole (SMBH), and/or by a burst of activity due to young, massive stars. It has been found that LIRGs and ULIRGs are associated with interacting and merging galaxies, respectively, and the interaction between the galaxies is assumed to provide large amounts of dense molecular gas that eventually reach the central regions of the galaxies, where they are responsible for triggering massive star formation and possibly accretion onto a SMBH [5]. However, not all the accumulated gas is expected to be accreted directly onto the putative SMBH, since the removal of the angular momentum of the gas is very inefficient [13]. The angular momentum that is not removed will then permit the accreted gas to form a reservoir, namely a nuclear disk in the central ∼100 pc around the AGN (e.g., and references therein] [15, 9]). Furthermore, if the gas in the nuclear starburst is dense enough, vigorous star formation is expected to occur, which can be detected via, e.g., high-angular resolution observations of recently exploded supernovae (e.g., in the LIRG Arp 299 [12], or the ULIRG Arp 220 [10]).

A scenario for (U)LIRGs was proposed by [9], where a nuclear disk is supported by the turbulent pressure of SNe. In their model, the turbulence due to supernova activity transports the angular momentum toward the central pc-scale region. One of the implications of the model developed by [9] is that the BH growth rate depends on the spatial distribution of both young stars and SNe in the nuclear disk.

We have used high-angular radio observations from the literature, as well as data obtained by us, of three starburst galaxies in the local universe (M82, Arp 299-A, and Arp 220) to analyze the radial distribution of CCSNe/SNRs in their central few hundred parsecs, which may have strong implications for the (co)-evolution of AGN and (nuclear) starbursts in galaxies, in general, and in (U)LIRGs in particular.

2 The radial distribution of SNe in nuclear starbursts

The radial distribution of SNe[1] on galactic scales has been thoroughly studied [2, 14, 1, 7]. Optical observations have been very useful for this purpose, as dust extinction plays a minor role in the external regions of most galaxies. However, the dust-enshrouded environments of the nuclear regions in (U)LIRGs, as well as the need for milliarcsecond angular resolution to pinpoint individual SNe, have prevented this kind of studies in the central regions of local (U)LIRGs. Fortunately, both issues –obscuration and (angular) resolution– can be overcome by means of Very Long Baseline Interferometry (VLBI) radio observations of the central regions of (U)LIRGs, since radio is dust-extinction free, and VLBI provides milliarsecond angular resolution.

2.1 Methods

We used VLBI observations to probe the radial distribution of SNe in the nuclear regions of Arp 299-A and Arp 220, as well as MERLIN, VLA, and VLBI observations towards M82. For each galaxy, we fitted the surface density profile of the SNe to two different disk profiles: (i) an exponential disk, $\Sigma^{SN} = \Sigma_0^{SN} \exp{(-\tilde{r}/\tilde{h}_{\rm SN})}$, and (ii) a disk with a power-law density profile with radius, $\Sigma^{SN} = \Sigma_0^{SN} (r/r_{\rm out})^{-\gamma}$. The first case (exponential disk) assumes that the SN distribution follows the radial surface-brightness density in spiral disks [6], while the second one (power-law disk) was used to probe the profiles predicted by numerical simulations [15]. The notation follows the one used in [7], where Σ_0^{SN} is the surface density of SN at the center, $\tilde{r}$ is the normalized radius, and $r_{\rm out}$ is the radius of the farthest SN analyzed, considered here to be the outer boundary of the putative nuclear disk. The main parameters that are obtained from those fits are the scale length, $\tilde{h}_{\rm SN}$, and the index of the power-law

[1]We will use here the term SNe to denote both CCSNe and SNRs.

Table 1: Scale length parameters for the studied galaxies

Nucleus	$\tilde{h}_{\mathrm{SN}}/10^{-3}$	h_{SN} (pc)	γ
Arp 299-A	$1.9^{+1.9}_{-0.8}$	$29.3^{+29.6}_{-13.7}$	$1.1^{+0.2}_{-0.2}$
Arp 220 East	$3.1^{+2.0}_{-0.9}$	$22.2^{+14.4}_{-6.2}$	$1.0^{+0.2}_{-0.3}$
Arp 220 West	$3.4^{+1.6}_{-1.5}$	$24.4^{+11.2}_{-10.8}$	$0.8^{+0.3}_{-0.2}$
Arp 220 E+W	$3.3^{+0.7}_{-0.9}$	$23.4^{+4.7}_{-6.6}$	$0.8^{+0.1}_{-0.2}$
A299 + A220	$2.0^{+0.3}_{-0.4}$	$20.9^{+2.6}_{-2.3}$	$0.9^{+0.1}_{-0.1}$
M82	$\left(2.8^{+0.9}_{-0.7}\right) \times 10^{1}$	$144.4^{+21.5}_{-17.5}$	-
[7] sample	$\left(2.9^{+0.2}_{-0.1}\right) \times 10^{2}$	-	-

profile, γ, of the putative nuclear disks in the central regions of these galaxies.

Following a similar analysis as the one described in [7], we determined the number of sources in concentric rings around the center of the galaxy and fitted the data to both an exponential and a power-law disk, as described above.

Since the supernova samples for all our three galaxies are of relatively small size, resulting in some small size bins, the actual uncertainties in the fits could be larger than formally obtained from a single fit. To assess the robustness of our fitting procedure, we performed a series of Monte Carlo (MC) simulations. For each galaxy, we generated 10 000 mock supernova samples, whose values were uniformly distributed within the uncertainty of each data point, and fitted them. In this way, we obtained a distribution of 10 000 different fitting values for the scale-length parameter, $\tilde{h}_{\mathrm{SN}}$, and the power-law index, γ, for each galaxy. This approach allowed us to obtain more reliable values of those parameters, since no assumption was made about the Gaussianity of the distributions of both the scale length and power-law index, or of their errors. We then used the median value of the distribution of our MC values to characterize $\tilde{h}_{\mathrm{SN}}$ and γ, and set the uncertainty in these parameters at the 90% confidence level. To test our method, we reanalyzed the sample of [7] for 239 CCSNe within 216 host galaxies, and obtained a value of $\tilde{h}_{\mathrm{SN}} = 0.29^{+0.02}_{-0.01}$, which is in excellent agreement with their estimate, and confirms the robustness of our analysis.

3 Results and discussion

Our main results are summarized in Table 1 and Fig. 1, where we show the scale lengths, index of the power-law SN profile, and the radial distribution of SNe for the three galaxies discussed here, as well as for the sample of spiral galaxies from [7].

We note that the scale lengths for the exponential disk fits to the radial distribution of SNe in the nuclear regions of the starburst galaxies, are at least an order of magnitude smaller that those obtained by [7] for the whole disks of spiral galaxies. In particular, $\tilde{h}_{\mathrm{SN}}$ is two orders of magnitude smaller in the case of Arp 299-A and Arp 220. Correspondingly, the

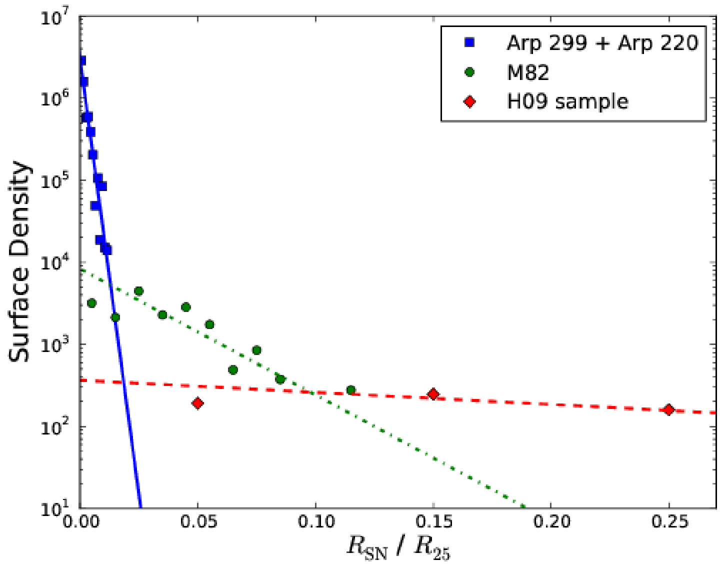

Figure 1: Radial distribution of SNe for (nuclear) starbursts and spiral galaxies. The data correspond to the combined Arp 299-A + Arp 220 sample (blue squares), M82 (green circles), and the [7] sample of spiral galaxies (red diamonds), and the fitted lines are for Arp 299-A + Arp 220 (solid line), M82 (dotted-dashed line), and [7] (dashed line). For the sake of clarity, only the innermost part of the [7] sample is shown in the plot.

physical sizes inferred for the scale lengths of the nuclear disks (col. 3 in Table 1) are much smaller than for galactic disks: ∼20–30 pc for Arp 299-A or Arp 220, which is similar to the size derived for the nuclear starburst of the LIRG NGC 7469 [4], using CO interferometric observations, and ∼160 pc for M82, which is also similar to the scale-length of the nuclear disk in the ULIRG/QSO Mrk 231 [3].

We show in Fig. 1 the radial distribution of SNe in our three starburst galaxies and, for comparison, also for spiral galaxies (from the [7] sample), along with the fits to these data. We note the clear existence of three different regimes: one characterized by a very steep profile of the surface number density of SNe, which is typical of strong, nuclear starbursts (Arp 299-A+Arp 220); a second, less steep profile, as indicated for the (circum)nuclear starburst in M82; and a third, flatter profile, which is typical of very large disks, such as those in spiral galaxies ([7] sample). These results suggest that the surface density of SNe, hence of available gas to convert into stars, reaches a maximum in the vicinities of the SMBH in LIRGs and ULIRGs. We also show in col. 4 of Table 1 the fits to a power-law disk profile, consistent with the fiducial value of $\gamma = 1$ used by [15] and [9] for the nuclear disk, and appears to yield further support to their modeling.

We have modeled for the first time the radial distribution of SNe in the nuclear starbursts of M82, Arp 299-A, and Arp 220, and derived scale-length values for exponential disks, which are in the range between ∼20 pc and ∼140 pc. We have also modeled these SNe distributions as power-law disk profiles, and found that they agree with state-of-the art numerical simulations of nuclear disks around SMBHs. We interpret our results as evidence of nuclear disks around the centers, i.e., AGNs, of starburst-dominated galaxies and also support for evolutionary scenarios where a nuclear disk of size $\lesssim 100$ pc is formed in LIRGs and ULIRGs [9]. In particular, the scale-length obtained for the LIRG Arp 299-A and the LLAGN nature of its SMBH [11], suggests that its nuclear disk is likely supported by gas pressure, such that the accretion onto the SMBH is smaller than for a turbulent-supported disk. It is very likely that this is also the case for the ULIRG Arp 220. Future deep VLBI observations of a significantly large sample of (U)LIRGs, which would result in the discovery of new SN factories, will be of much use for deriving statistically significant results on the size of nuclear disks, and thus setting useful constraints on (co)-evolutionary scenarios.

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