Ongoing Star Formation In AGN Host Galaxy Disks: A View From Core-collapse Supernovae

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ABSTRACT

The normalized radial distribution of young stellar populations (and cold gas) in nearby galactic disks is compared between AGN host galaxies and starforming galaxies (both with Hubble types between S0/a and Scd) by using type II supernovae (SNe) as tracers. A subset of 140 SNe II with available supernova position measurements are selected from the SAI-SDSS image catalog by requiring available SDSS spectroscopy data of their host galaxies. Our sample is finally composed of 46 AGNs and 94 star-forming galaxies. Both directly measured number distributions and inferred surface density distributions indicate that a) the SNe detected in starforming galaxies follow an exponential law well; b) by contrast, the SNe detected in AGN host galaxies significantly deviate from an exponential law, which is independent of both morphological type and redshift. Specifically, we find a detection deficit around $R_{SN}/R_{25,cor} \sim 0.5$ and an over-detection at outer region $R_{SN}/R_{25,cor} \sim 0.6 - 0.8$. This finding provides a piece of evidence supporting that there is a link between ongoing star formation (and cold gas reservoir) taking place in the extended disk and central AGN activity.

Key words: galaxies: active — galaxies: Seyfert — supernovae: general

1 INTRODUCTION

It is now generally believed that active galactic nuclei (AGNs) play an important role in galaxy formation and evolution. The growth of the central supermassive black hole (SMBH) is suggested to be related to the formation of the bulge of the host galaxy where the SMBH resides. This evolutionary scenario is supported by the well-established Magorrian relationship (e.g., Magorrian et al. 1998; Tremaine et al. 2002; Ferrarese et al. 2006), and by the fact that both star formation and AGN activity show similar evolutions from $z \sim 1$ to the current epoch (e.g., Ueda et al. 2003; Silverman et al. 2008).

So far, two kinds of mechanisms have been proposed to explain the co-evolution of AGNs and their host galaxies. One possible mechanism is that both AGN activity and formation of the bulge are triggered by a merger of two gas rich galaxies (e.g., Granato et al. 2004; Springel et al. 2005; Hopkins et al. 2005). Reichard et al. (2009) recently found that more active AGNs with younger circumnuclear stellar populations are on average associated with more lopsided host galaxies. An alternative possibility is the gas inflow caused by the large scale gravitational asymmetry of the host galaxies, such as a bar structure. Both mechanisms can produce an inflow of gas by transporting the angular momentum out of the gas. The falling gas not only forms stars at the central region, but also fuels the central SMBH. The feedback of AGNs onto their host galaxies will likely regulate the growth of the bulge by heating and expelling the surrounding gas through strong radio jets or other AGN-driven outflows (e.g., Croton et al. 2006; Hopkins & Hernquist 2006; Di Matteo et al. 2005).

The distribution of cold gas in AGN host galaxies is therefore crucial to the study of the co-evolution issue. In addition to directly detecting the gas distribution by the HI line emission, the gas distribution can be approximately (and reasonably) substituted by the spatial distribution of young stellar populations. Although young stellar populations are frequently identified in the host galaxies of some local AGNs (e.g., Cid Fernandes et al. 2001; Gonzalez Delgado et al. 2001; Zhou et al. 2005; Wang & Wei 2006; Mao et al. 2009), their spatial distribution in the host galaxies is still poorly understood. Combining the GALEX near-UV survey with the SDSS survey, Kauffmann et al. (2007) recently found that in the local universe, although the AGN activity is strongly correlated with the age of the stars in the bulges (see also in Wang & Wei 2008; Kewley et al. 2006; Wild et al. 2007), the most active AGNs
are always associated with the bluest outer disks. However, not all the galaxies with blue outer disks have an active AGN. This result therefore motivates the authors to believe that it could be understood if the amount of gas transported inward from disk is a variable.

In this paper, we investigate the co-evolution issue by comparing the radial distribution of the core-collapse supernovae (cc-SNe) detected in AGN host galaxies with the similar distribution of the cc-SNe detected in starforming galaxies. Because cc-SNe are generally accepted to be produced by the explosion of massive stars ($\geq 8 - 10 M_{\odot}$) at the end of their lifetime $\lesssim 10^7$yr (e.g., Woosley et al. 2002), the radial distribution of cc-SNe reasonably represents the distribution of young stellar populations. The advantage of this approach is that the result does not strongly depend on the spatial resolution of the observations.

2 SAMPLE SELECTION AND ANALYSIS

At first, the spectroscopic data from the SDSS Data Release 6 are cross-matched with the SAI-SDSS image SNe catalog. In our cross-matching, we require that a) the angular offset of an individual SN measured from the center of the host galaxy is less than 1; b) the difference in redshift ($\Delta z$) between the SN and corresponding host galaxy is less than 0.01. The cross-matched sample in total contains 620 events, covering all three main supernova types Ia, Ib/c and II. Among the sample, more than 97% of the events show $\Delta z < 0.003$, which means that only for a few outliers, the recessional velocity difference between the SNe and their host galaxies is inferred to be larger than 900km s$^{-1}$. We further limit the sample to the SNe whose host galaxies have measured photometric diameters and ratios of their minor and major axes. To ensure adequate sample size and minimize the bias introduced by morphology types and host galaxy luminosity, we finally restrict our sample to the SNe whose a) host galaxies show late morphology types ranging from S0/a to Scd (i.e., the T parameter is between 0 and 6.5), b) redshifts are less than 0.045. Given that the SNe II are much more common than the SNe Ib/c, only the SNe II are included in the analysis presented here.

The spectroscopic data taken by the SDSS are then analyzed to diagnose the central power source for these galaxies. For each narrow emission-line galaxy, the underlying stellar absorption features are first removed from the observed spectrum by the principal component analysis method (see Wang & Wei 2008 for details). The starlight-subtracted spectrum is then used to measure emission line fluxes by the splot task in the IRAF package. These emission-line galaxies are separated into AGNs and starforming galaxies according to the widely used BPT diagram (i.e., the [OIII]/H$\alpha$ vs. [NII]/H$\alpha$ diagnostic diagram, Baldwin et al. 1981; Veilleux & Osterbrock 1987). The empirical demarcation line proposed by Kauffmann et al. (2003) is adopted in the classification. Finally, there are in total 46 AGNs (hereafter AGN sample) and 94 starforming galaxies (hereafter SF sample) passing the above criteria. Note that the SNe II host AGNs are dominated by type II AGNs that are on average a factor of 100 fainter in bolometric luminosity than typical type I AGNs (see recent review in Ho 2008). The classifications of these galaxies are illustrated in Figure 1. AGNs and starforming galaxies are symbolized by red-open squares and blue-solid squares, respectively.

Following previous studies (e.g., Petrosian & Turatto 1990; Bartunov et al. 1992; van den Bergh 1997; Petrosian et al. 2005), the supernova relative distance ($R_{SN}/R_{25,cor}$) measured from the center of the host galaxy is calculated for each SN by using the same method used in Tsvetkov et al. (2004), where the projected distance of the SN from the center of its host galaxy is $R_{SN} = \sqrt{(\Delta \alpha)^2 + (\Delta \delta)^2}$. At the direction along the position angle of the SN, $R_{25,cor}$, the projected radius of the galaxy up to surface density of 25mag arcsecond$^{-2}$ corrected for the inclination of the galaxy, is calculated as

$$R_{25,cor} = \frac{d_{25}}{2\sqrt{\cos^2 \theta + b^2 \sin^2 \theta}}$$

where $d_{25}$ is the measured galaxy photometric diameter up to surface density of 25mag arcsecond$^{-2}$, $\theta$ the position angle of an individual SN, and $b$ the ratio between major and minor axes.

3 SUPERNOVAE IN AGN HOST GALAXIES: A SIGNIFICANT DEVIATION FROM AN EXPONENTIAL LAW

Even though the two sub-samples are selected by taking the cuts in morphological type and redshift, the two sub-samples do not show identical distributions of their morphological types and redshifts. To alleviate the possible biases, we assign a weight for each galaxy in the SF sample. At first, the distributions of the morphological types are compared between the two sub-samples. A weight is assigned to each galaxy in the SF sample by requiring the two distributions are identical. A second weight could be obtained through the similar procedure but for redshifts. In each procedure, we adopt a bin size that ensures each bin contains at least one object. The total weight associated with each galaxy in the SF sample is derived by multiplying the two weights.

By taking the calculated weights into account, Figure 2 compares the histogram of the radial distribution of $R_{SN}/R_{25,cor}$ of the SNe II discovered in the AGN host galaxies with the similar plot of the SNe II discovered in the starforming galaxies. The overplotted error-bar for each bin corresponds its 1$\sigma$ Poisson noise. Both radial distributions show a deficit of SNe within the region $R_{SN}/R_{25,cor} < 0.2$ (see also in e.g., Petrosian et al. 2005; Hakobyan et al. 2009), which is an observational bias, i.e., the Shaw (1979) effect. It is a challenging task to uncover a supernova event from galactic centers, both because of the luminous background and because of the possible heavy extinction in the galactic centers.

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† The catalog is described in Prieto et al. (2008), and can be downloaded from http://www.astronomy.ohio-state.edu/~prieto/snhosts/.

‡ IRAF is distributed by the National Optical Astronomical Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
One can see from the figure that, in the outer disk, the $R_{SN}/R_{25,cor}$ distribution of the SNe II discovered in the starforming galaxies decreases smoothly with the radial distance measured from the galactic centers, which bears a strong similarity to the starlight distribution in the galactic disk. Hakobyan et al. (2009) suggested that the distribution of the relative distance of cc-SNe from the centers of their host galaxies could be appropriately described by an exponential law. Compared with the case in the starforming galaxies, the SNeII discovered in AGN host galaxies show a different radial distribution with both an evident reduced fraction at $R_{SN}/R_{25,cor} \sim 0.4$ and a clear over-detection in the outer region within $R_{SN}/R_{25,cor} \sim 0.6-0.8$, i.e., a bimodal radial distribution. As shown in the figure, both features are significant at a confidence level no less than 1σ. We further roughly quantify the peak of the over-detection to be at $R_{SN}/R_{25,cor} \sim 0.6$. By considering the objects with $R_{SN}/R_{25,cor} \leq 1$, the Gehan’s Generalized Wilcoxon two-sample statistical tests show the two distributions are drawn from the same parent population at a confidence level of 4% (for permutation variance) and 5% (for hypergeometric variance). A two-side Kolmogorov-Smirnov test is performed on both samples. The test yields a max discrepancy of 0.29 with a corresponding probability that the two samples match of 1.3%.

It is noted that a similar bimodal distribution is also recently identified in Hakobyan et al. (2009) who studied the relative radial distribution of the cc-SNe from the Asa- go catalog. By separating the sample into two groups, i.e., active- and non-active galaxies, our study indicates that the second peak shown in the Figure 4 of Hakobyan et al. (2009) is in fact mainly contributed by AGNs.

Figure 3 plots the relative distances of the SNe II calculated from the centers of their hosts vs. the morphological type of the host galaxies (the upper panel) and redshifts (the lower panel). The objects in the AGN sample and in the SF sample are shown by red crosses and green circles, respectively. In both panels, starforming galaxies are continually distributed in the diagram. By contrast, the bimodal radial distribution can still be clearly identified for AGNs even when one compares the relative distances between AGNs and starforming galaxies at a given morphological type or redshift. There is an obvious gap at $R_{SN}/R_{25,cor} \sim 0.4-0.5$ separating the AGNs into two sub-groups. This figure therefore strongly suggests that the bimodal distribution revealed for AGNs is robust, i.e., not correlated to morphological type and luminosity of the supernova host galaxies.

As an additional test, the bimodal radial distribution of the SNe II discovered in AGN host galaxies is still significant if we examine the issue more physically. Figure 4 shows the surface density distribution of the SNeII as a function of $R_{SN}/R_{25,cor}$ for both AGN and SF samples. The surface density is calculated as $\Sigma_{SN} = N/S$ for each distance bin, where $S = 2\pi r \Delta r$ is the area of a circle with a radius $r$ and a
width $\Delta r$, and $N$ the number of SNe detected within the circle. The distributions plotted in Figure 1 are rebinned into a single bin for the outer region $R_{SN}/R_{25,cor} > 1$. In Figure 4, the AGN and SF samples are symbolized by red-triangles and green-open-circles, respectively. The 1σ Gaussian uncertainty over-plotted in the diagram is calculated according to the error tables given in Gehrels (1986). The surface density of the SNe II discovered in AGN host galaxies deviates from an exponential profile significantly. Secondly, our sample is selected by requiring individual SN to lie within 1 arcminute of the corresponding host galaxy center. These selection causes the sample to be biased against the SNe discovered at the edge of very nearby host galaxies. Note that the main conclusion presented in the current paper can not be affected by the bias since both AGN- and starforming sub-samples are selected by the same method.

To illustrate the deviation from an exponential profile for the AGN sample, we vertically shift the best fitting derived for the SF sample by an amount of -0.31 dex ($= \log(47/95)$) by fixing the exponential index. The shifted exponential model is drawn by a red short-dashed line in Figure 4. The model obviously provides a good match for the points at the two ends (by excluding the two points with $R_{SN}/R_{25,cor} < 0.2$ as well). Comparing the model with the calculated surface density allows us to identify an over-density at the region $R_{SN}/R_{25,cor} \sim 0.6 - 0.8$ and a low density at $R_{SN}/R_{25,cor} \sim 0.4$, which agrees with the analysis based upon the directly measured number distributions.

4 CONCLUSION AND DISCUSSION

Because SNe II are generated from the explosion of massive stars ($\geq 8M_\odot$), the SNeII radial distribution in their host galaxies reasonably reflects not only the radial distribution of young stellar populations, but also the radial distribution of cold gas, assuming a uniform supernova rate. By comparing the radial distributions of the SNeII detected in AGNs and the similar distribution of the SNeII detected in starforming galaxies, we find that the supernova radial distribution in AGN host galaxies deviates greatly from the exponential model that can describe the radial distribution.
in starforming galaxies well. Both directly measured number distribution and inferred surface density indicate that SNe detected in AGN host galaxies show a bimodal distribution as a function of radius.

The comparison of the radial distributions of the SNe II detected in the two types of supernova host galaxy allows us to argue that the existence of the AGN activities is connected with the gas reservoir located in the extended galactic disk, which agrees with the previous studies. Kauffmann et al. (2007) identified a UV-light excess in the extended disk for local AGN host galaxies. Hunt et al. (1999) suggested that the AGN host galaxies show a larger gas fraction in their disk than non-active galaxies. Using deep imaging from Spitzer and GALEX, Zheng et al. (2009) suggested that the star formation in massive galaxies at $z < 1$ mainly takes place in the isolated disks. Moreover, stellar rings in the disks are more frequently identified in AGN host galaxies than in starforming galaxies (Hunt & Malkan 1999). By examining the spatially resolved stellar populations of 8 AGNs at $z \sim 1$, Ammons et al. (2009) arrived at a conclusion that the strong type II AGNs are associated with extended star formation activities.

The star formation occurring in non-active galaxies and star formation associated with SMBH accretion appear to be different events with different origin. The radial distribution of the SNe II in the starforming galaxies can be well modelled by an exponential model, which means the gas distribution in these galactic disks is not significantly disturbed. Some particular dynamical mechanisms are necessary in AGN host galaxies to redistribute gas to trigger both large-scale star formation occurring in the outer disk and central SMBH activity (and also associated circumnuclear star formation).

So far, several mechanisms have been proposed to link the central AGNs with the outer parts of their host galaxies. Kauffmann et al. (2007) proposed that the gas distributed in the outer disk of AGN host galaxies could stem from the accretion of gas from an external source. In addition, the redistribution of gas could be resulted from minor merger or major merger of two galaxies (e.g., Martini 2004 and references therein). Recent numerical simulations indicated that the stars and gas could survive to re-form a disk in the merger of two gas rich galaxies (e.g., Hopkins et al. 2009; Hammer et al. 2005). In the merger process, the gas within some characteristic radius loses its angular momentum quickly, and sinks into the galactic central region by the gravitational attraction. The gas that survives outside of the characteristic radius will descend to form a new disk if the strong AGN feedback is taken into account. The multiple disks produced by interactions are indeed observed in individual local Seyfert galaxies, e.g., Mark 315, a Seyfert 1.5 galaxy (Ciroi et al. 2005). Reichard et al. (2009) recently reported a connection between AGN activity and lopsidedness of their host galaxies. An outer loop and an arc with blue colors were observed in Seyfert 1.8 galaxy Mark 334 at an radius $r \sim 20-30'$ from the center (Smirnova & Moisseev 2009). The blue colors suggest the existence of young stellar populations (~0.5-1 Gyr) that are formed in the interaction process. Adopting the characteristic radius of the galaxy $R_{25} \approx 50''$ estimated from the Figure 4 in Smirnova & Moisseev (2009), the relative distance of the outer loop and arc is inferred to be $\sim 0.4 - 0.6$.

Besides the merger scenario, it is now generally believed that the bar-driven gas inflow is related to the formation of the gas rings (Buta & Combes 1996). Theoretical and N-body simulation studies indicated that the gravitational asymmetry caused by the bars transports gas angular momentum. The migration of the angular momentum results in a gas inflow within the corotation radius and an outflow of gas out of the corotation radius (e.g., Sellwood & Wilkinson 1993; Athanassoula 2003). The gas redistribution fuels central AGNs and circumnuclear starbursts, destroys the bars (e.g., Bournaud & Combes 2002), and regulates the gas into a stable configuration (e.g., rings) by itself.

ACKNOWLEDGEMENTS

We thank the anonymous referee for his/her valuable comments and suggestions that are helpful in improving the paper. The authors thank James Wicker for help with language. This study uses the SDSS archive data that was created and distributed by the Alfred P. Sloan Foundation. This work was supported by the National Science Foundation of China (under grants 10673014 and 10803008) and by the National Basic Research Program of China (grant 2009CB824800).

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