FORMATION OF A MASSIVE BLACK HOLE AT THE CENTER OF THE SUPERBUBBLE IN M82

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ABSTRACT

We performed \textsuperscript{12}CO (1–0), \textsuperscript{13}CO (1–0), and HCN (1–0) interferometric observations of the central region (about 450 pc in radius) of M82 with the Nobeyama Millimeter Array and have successfully imaged a molecular superbubble and spurs. The center of the superbubble is clearly shifted from the nucleus by 140 pc. This position is close to that of the massive black hole (BH) of \( \gtrsim 460 \, M_\odot \) and the 2.2 \( \mu \)m secondary peak (a luminous supergiant-dominated cluster), which strongly suggests that these objects may be related to the formation of the superbubble. Consideration of star formation in the cluster based on the infrared data indicates that (1) the energy release from supernovae can account for the kinetic energy of the superbubble, (2) the total mass of stellar-mass BHs available for building up the massive BH may be much higher than 460 \( M_\odot \), and (3) it is possible to form the middle-mass BH of \( 10^5–10^6 \, M_\odot \) within the timescale of the superbubble. We suggest that the massive BH was produced and is growing in the intense starburst region.

Subject headings: black hole physics — galaxies: individual (M82, NGC 3034) — galaxies: ISM — galaxies: starburst — ISM: bubbles

1. INTRODUCTION

A starburst is a star formation event with a high star formation efficiency. This usually occurs in the galactic nuclear/central regions. Starbursts and successive supernova explosions cause drastic changes in the kinematic and physical conditions of the interstellar medium, and they produce (expanding) superbubbles, chimneys, and/or large-scale outflows. There is observational evidence for these structures in hot and/or atomic gas in many galaxies (e.g., Fabian 1989; Tenorio-Tagle & Bodenheimer 1988), but there is much less clear evidence in molecular gas. Starburst phenomena in the nuclear regions are also thought to be closely related to active galactic nuclei (AGNs) powered by massive black holes (MBHs; more massive than a stellar-mass black hole [BH]) that fuel the AGNs and/or that cause the growth of more MBHs. One question is still largely unresolved: Can starbursts produce the seeds of MBHs or middle-mass BHs?

The nearby (3.25 Mpc; Sandage & Tammann 1975) irregular galaxy M82 (NGC 3034) has kiloparsec-scale bipolar outflows that can be seen by optical emission lines (e.g., Shopbell & Bland-Hawthorn 1998) and by X-ray (e.g., Bregman et al. 1995; see Fig. 1a). This outflow is believed to be made by frequent supernova explosions at the central region as a consequence of starbursts. Recent X-ray studies have found evidence of an MBH with a mass of \( \gtrsim 460 \, M_\odot \) in the starburst region (Matsumoto & Tsuru 1999; Ptak & Griffiths 1999). In this region, however, strong dust absorption prevents observational evidence for these structures in hot and/or atomic gas in many galaxies (e.g., Fabian 1989; Tenorio-Tagle & Bodenheimer 1988), but there is much less clear evidence in molecular gas. Starburst phenomena in the nuclear regions are also thought to be closely related to active galactic nuclei (AGNs) powered by massive black holes (MBHs; more massive than a stellar-mass black hole [BH]) that fuel the AGNs and/or that cause the growth of more MBHs. One question is still largely unresolved: Can starbursts produce the seeds of MBHs or middle-mass BHs?

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2. OBSERVATIONS

Aperture synthesis observations of the central region of M82 were carried out in the \( ^{12} \)CO, \( ^{13} \)CO, and HCN \( J = 1 \rightarrow 0 \) lines (rest frequency = 115.271, 110.201, and 88.632 GHz, respectively) with the Nobeyama Millimeter Array (NMA) during 1997 November–1999 March. All the images were obtained using three configurations of six 10 m antennas that are equipped with tunerless SIS receivers (Sunada, Kawabe, & Inatani 1994), and the system noise temperatures in the single sideband were about 950, 850, and 450 K at 115, 110, and 89 GHz, respectively. As a back end, we used an XP-type spectrocorrelator, the ultrawide-band correlator (UWBC; Okumura et al. 2000), with a total bandwidth of 512 MHz over 256 channels for the \( ^{12} \)CO observations (corresponding to a 1300 km s\(^{-1}\) bandwidth with a 5.2 km s\(^{-1}\) velocity resolution) and with a total bandwidth of 1024 MHz over 128 channels for the \( ^{13} \)CO and HCN observations (corresponding to 2800 and 3500 km s\(^{-1}\) bandwidths with 22 and 27 km s\(^{-1}\) velocity resolutions, respectively). The bandpass calibration was done with 3C 273, and 0923+392 was observed every 10 minutes as a phase and amplitude calibrator. The flux scale of 0923+392 was determined by comparisons with Mars and Uranus and has an uncertainty of \( \sim 20\% \).

3. EXPANDING MOLECULAR SUPERBUBBLE

The overall distribution in the \( ^{12} \)CO total integrated intensity map shows diffuse spurs north and south (minor-axis direction) of the galaxy, in addition to the previously identified (Shen & Lo 1995) three prominent peaks (the so-called northeast and southwest lobes and a central peak). These spurs trace the dark filaments that can be seen in optical B-band images (Alton, Davies, & Bianchi 1999; see Fig. 1b). Similar structures have been detected farther out in the filaments (Nakai et al. 1987; Kuno & Matsuo 1997; Alton et al. 1999) that are connected to the large-scale H\( \alpha \) and X-ray outflow (Shopbell & Bland-Hawthorn 1998; Bregman et al. 1995; see Fig. 1a), but ours is the first detection close to the disk.

A position-velocity (PV) diagram of \( ^{12} \)CO data cut along the major axis of the galaxy (Fig. 2b) shows an arclike deviation...
from rigid rotation between the central peak and the southwest lobe. Such deviations are common features of expanding H I superbubbles (Deul & den Hartog 1990). In addition, recent literature also suggests that this deviation implies the existence of a molecular superbubble (Neininger et al. 1998; Weiss et al. 1999; Wills et al. 1999). However, shell structures have not been detected in any spatial image so far, and Weiss et al. (1999) concluded that the superbubble had already broken toward the minor-axis direction of this galaxy. We made a channel map, binning over the velocity range of $V_{LSR} = 118–212$ km s$^{-1}$, which corresponds to a range that deviates from the rigid rotation (Fig. 1c). The map clearly shows a shell-like structure, with a diameter of $\sim$210 pc $\times$ 140 pc ($\sim$14° $\times$ 9°) elongated toward north-south direction, between the two peaks. This structure is also visible in other molecular lines such as $^{13}$C$\text{O}$ (Fig. 1d) and HCN (Fig. 1e). These images indicate that the superbubble still has not broken out of the galactic disk. Around the superbubble, however, there are some spurs connected to the shell structure, so that it may be possible that some parts of the superbubble were already broken.

If we assume that the shell structure is the result of edge brightening (Wills et al. 1999), the southern part of the shell should be moving perpendicular to the line of sight with a nearly rigid rotation velocity, which corresponds to the systemic velocity of the molecular superbubble. Indeed, the velocity field of the southern shell is very close to a rigid rotation (Fig. 2c).
Using the intensity ratios between the $^{12}$CO line and the $^{13}$CO and HCN lines, we calculated the CO-to-H$_2$ conversion factor based on the large velocity gradient approximation (Sakamoto 1999). The resultant conversion factor is $(1.4 \pm 0.6) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$, which is consistent with the previous observations of $(1.0-1.2) \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ (Wild et al. 1992; Smith et al. 1991). Hence, we adopted our estimated value, and the calculated molecular superbubble mass would be $\sim 1.8 \times 10^8 M_\odot$. From this molecular gas mass and the expansion velocity, we derive a kinetic energy for the superbubble of $\sim (0.5-2) \times 10^{53}$ ergs, which is equivalent to the total energy of $\sim 10^3-10^4$ supernovae. We adopted our estimated value $\sim 10^4$ ergs, which is similar to ours, although their estimation has a large ambiguity in the volume of the material swept up by the explosion.

4. Massive Black Hole Inside the Superbubble

At the center of the superbubble, there is a hard X-ray variable point source and a 2.2 $\mu$m secondary peak (Fig. 1c); hard X-ray observations with ASCA indicate that there is a strong point source located in the central region of M82. This source shows time variability in its intensity, which indicates the existence of an MBH with a mass of $\sim 460$ to $2 \times 10^8 M_\odot$ (Matsumoto & Tsuru 1999; Ptak & Griffiths 1999). Comparing the ROSAT image (Bregman et al. 1995; Stevens, Strickland, & Wills 1999) with the false ROSAT image made from ASCA data (using a similar energy band to that of ROSAT), it was found that the position of the hard X-ray variable source is consistent with that of the X-ray peak detected with ROSAT (Matsumoto & Tsuru 1999). A detailed comparison between the location of this point source and our newly obtained $^{12}$CO map reveals that the X-ray point source is located at the center of the superbubble. Recent high-resolution X-ray observations with Chandra show that there is a variable source inside the superbubble with a peak luminosity of $\sim 9 \times 10^{50}$ ergs s$^{-1}$, assuming that this source has the same spectrum as the ASCA variable source (Matsumoto et al. 2000). This result also supports the conclusion that there is an MBH inside the superbubble. On the other hand, the emission from the 2.2 $\mu$m secondary peak (Dietz et al. 1986; Lester et al. 1990) seems to be dominated by luminous supergiants (Joy, Lester, & Harvey 1987), which suggests that it is a late-phase dense starburst cluster.

Since these objects are located close to the center of the superbubble, it is natural to think that these objects are related to the superbubble’s formation. We therefore discuss the possibility that the starburst at the 2.2 $\mu$m secondary peak produces the superbubble and the MBH. We first calculated the stellar population of this 2.2 $\mu$m secondary peak cluster by assuming an initial mass function (IMF), and then we estimated the starburst evolution as follows. The luminosity of the 2.2 $\mu$m secondary peak with an extent (FWHM) of 4$''$ (McLeod et al. 1993) is equivalent to $\sim 1500$ M$_2$ supergiants. We assume that stars with initial masses larger than $30 M_\odot$ (short-lived stars with lifetimes of less than $2 \times 10^6$ yr; Lang 1998) have already exploded as supernovae and that the remaining stars with initial masses of $25-30 M_\odot$ are now M2 supergiants. Using an extended Millar-Scalo IMF (Kennicutt 1983) of dN/dm $\propto m^{-2.5}$ with lower and upper mass limits of 1 and 100, respectively, and assuming that there are 1500 stars whose masses are $25-30 M_\odot$, the total stellar.

Fig. 2.—PV diagrams of M82. The values for the color scale are indicated on the top of each figure. (a) $^{13}$CO integrated intensity map. The solid lines indicate the sliced regions for PV diagrams displayed below. The plus sign is the same as in Fig. 1b. (b) PV diagram at slice A. The solid line indicates a rigid rotation velocity. The region of the superbubble [around $\alpha$(B1950) = 9$^h$51$^m$43$^s$6] clearly deviates from the rigid rotation velocity. (c) PV diagram at slice B. The solid line indicates a rigid rotation velocity. Almost all of the gas at this slice is on the rigid rotation velocity.

In addition, the PV diagram shows that almost all of the molecular gas, except that of the superbubble, is on the rigid rotation (Fig. 2b). These reasons lead us to conclude that the expansion velocity of the superbubble is the largest velocity deviation from the rigid rotation seen in the PV diagram; the resultant expansion velocity is $\sim 100$ km s$^{-1}$. However, we cannot reject the possibility of an expansion velocity of $\sim 50$ km s$^{-1}$, which is the mean velocity deviation in the PV diagram (Weiss et al. 1999), so we use the velocity range of 50–100 km s$^{-1}$ for the following calculations. Using the velocity and the size of the superbubble derived above, the elapsed time from the explosion can be estimated as $\sim (1-2) \times 10^6$ yr. Weiss et al. (1999) also derived a similar timescale of $1 \times 10^6$ yr.

Next, we will estimate the energetics of the superbubble.
number and the total mass formed at the 2.2 μm secondary peak cluster would be about \(8 \times 10^5\) stars and \(2 \times 10^6 M_\odot\), respectively. The number of \(\geq 30 M_\odot\) stars that would have already exploded in this cluster is \(\sim 4 \times 10^3\), which is consistent with the estimated number of supernovae needed to create the superbubble \((10^5-10^6)\). The observational evidence and IMF calculations suggest that the expanding molecular superbubble may be the result of localized starbursts that occurred around the position of the 2.2 μm secondary peak.

We next discuss the possibility of making an MBH during a starburst in M82. If we assume that stars with initial masses of greater than 25 \(M_\odot\) would create stellar-mass BHs of almost the same mass (Brown & Bethe 1994), there would be \(\sim 4 \times 10^3\) BHs with a total mass of \(\sim 2 \times 10^5 M_\odot\) in the 2.2 μm secondary peak cluster. Assuming an isothermal sphere stellar density distribution (Lee 1995), about \(4 \times 10^5 M_\odot\) BHs would sink into the cluster center by dynamical friction within \(2 \times 10^6\) yr. This mass is well within the range of that of the MBH estimated from the hard X-ray observations. There is also a possibility of a star-star merger. If we assume a merging probability of 0.1% in the cluster, which is a similar probability to the simulations of stellar mergers in star clusters (Portegies Zwart et al. 1999), it is possible to make one \(\sim 700 M_\odot\) star, or several stars of a few hundred solar mass, in the cluster. Explosions of such very high mass stars can produce supernovae with \(\geq 10^{52}\) ergs, or even \(10^{54}\) ergs, of energy (e.g., Paczyński 1998), which can be seen as \(\gamma\)-ray bursts, and may possibly have created the superbubble and the MBH. If we set the lower limit of the BH mass \(M_{\text{BH}}\) in this cluster using the hard X-ray observations, and the upper limit using the total mass of the stars that already seem to have exploded \((\geq 30 M_\odot)\), the range of the BH mass would be from 460 to \(2 \times 10^5 M_\odot\). This mass range suggests that this MBH might be a middle-mass BH. Since the cluster mass \(M_{\text{cluster}}\) is calculated as \(2 \times 10^6 M_\odot\) using the IMF, the ratio of \(M_{\text{BH}}\) to \(M_{\text{cluster}}\) would be \(-3.6 \leq \log (M_{\text{BH}}/M_{\text{cluster}}) \leq -1.0\). As shown in Figure 3, this range is on the \(M_{\text{BH}} - M_{\text{cluster}}\) relation for galaxies with supermassive BHs (Magorrian et al. 1998).

Since there are many other clusters in the central region of M82, another question arises: Why is it that other clusters do not have MBHs? One possibility is the lack of stellar density. If their densities are small, the effect of dynamical friction or a star-star merging rate may decrease, and it may not be possible to make massive objects. The low-density clusters would also be affected by a tidal force (e.g., Taniguchi et al. 2000) and would tend to be smaller clusters that are not large enough to make massive objects. Another possibility is that the MBH was not created at the cluster but was the result of a minor merger with a satellite galaxy (e.g., Taniguchi et al. 2000). In this case, there are two possibilities for the agreement between the position of the MBH and that of the superbubble; one is that they accidentally overlap each other, and another is that the superbubble is created by the MBH. A BH merging with a compact object (neutron star, white dwarf, etc.) can cause a large energy release \((\sim 10^{54}\) ergs; Mészáros, Rees, & Wijers 1999). If the MBH meets with a cluster while sinking toward the galactic center, there are possibilities of merging with some compact objects, and as a result, energetic explosions would occur, and the superbubble would be made. These discussions still have large ambiguities because of the lack of detailed information; thus, further observations with many wavelengths/frequencies are needed.

In future, this middle-mass BH may increase its mass. Since massive stars still exist \((\sim 10^5 M_\odot)\) at the 2.2 μm secondary peak cluster, it is possible to feed stars and/or stellar-mass BHs to the middle-mass BH. Also, the middle-mass BH is still not at the dynamical center of M82, and it may sink down to the center with dynamical friction; there the mass is strongly concentrated. Therefore, there are many ways for the middle-mass BH in M82 to increase its mass and therefore grow to be a supermassive BH. Our results may give a new explanation as to the reason why some of the quasars are embedded in interacting (and therefore active star-forming) galaxies, and why strong \(\gamma\)-ray bursts and middle-mass BHs are located either in galactic nuclei or offset from them.

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![Fig. 3.—Correlation diagram between the masses of black holes (M_{BH}) and those of the host bulges or clusters (M_{bulge}) in galaxies. The error bar indicates the estimated mass range of the middle-mass BH in M82, assuming its host corresponds to the 2.2 μm secondary peak cluster. The upper limit of the middle-mass BH mass and the 2.2 μm secondary peak cluster mass have been estimated from IMF calculations, and the lower limit of the BH mass has been estimated from the hard X-ray observations. The crosses indicate the data taken from Magorrian et al. (1998), and the solid line is a linear fitting of their data. We did not include their upper limit data in this diagram. This figure clearly shows that the data of M82 follow the trend of the mass of the supermassive black holes and those of the host bulges.](image)
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