Star Formation Timescale in the Circumnuclear Starburst Ring of Barred Galaxy NGC 7552

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Abstract. We present the multiple line observations carried out with interferometry. We observed the circumnuclear region of the barred galaxy NGC 7552 in molecular lines tracing diffuse molecular gas (12CO J = 2 - 1; observed by SMA) and relatively dense molecular gas (HCN J = 1 - 0; observed by ATCA). We also reprocessed a published HI image which covers the entire galaxy to gain an analytical image with higher resolution.

The displacement between HCN (J = 1 - 0) and radio knots (3 cm continuum; ATCA archive data) is clearly seen in the circumnuclear starburst ring of NGC 7552. The propagation time derived from 12CO J = 2 - 1 and HI based rotation curve between the HCN (J = 1 - 0) and radio knots implies the timescale between the formation and death of massive stars. The timescale of NGC 7552 is about an order of magnitude shorter than 5 - 10 Myr timescale for OB stars to become supernovae. It is possible that star formation in the ring is top heavy, resulting in a shorter timescale.

1. Introduction

Over half of all spiral galaxies in the Local Universe exhibit large-scale bars [1]. Theory predicts that a galactic bar is able to transport disk molecular gas toward the center via dust lanes. In addition, observation in 12CO (1 - 0) also shows a correlation between the degree of central concentration of molecular gas and the bar strength [2]. The accumulation of molecular gas in central region of galaxies gives the chance to form stars. Therefore, it is not surprising that circumnuclear starburst rings are commonly seen in the centers of barred galaxies.

In this proceeding, we present the results of multi-line interferometric observations of NCC 7552. Since our lines trace different stages of star formation, the results allow us to calculate the star formation timescale in the circumnuclear ring.

2. Target

NGC 7552 is a face-on (i = 25°) barred galaxy with a distance of 22.3 Mpc at 23° 16′ 10.8″ -42d 35m 05s, corresponding to 1″ = 21 Mpc. The galaxy is a member of the galaxy group known as the Southern Grus Quartet. Figure 1 shows the optical image of NGC 7552 with different...
Figure 1. Optical B-band images of NGC 7552 taken at the CTIO, and retrieved from the NASA Extragalactic Database (NED). The left panels shows the image with more saturation, showing the spiral arms. The right panel with less saturation indicates the bar and dust lanes.

Figure 2. Radio continuum images of the circumnuclear starburst ring in NGC 7552 at 6 cm (left panel) and 3 cm (right panel), re-created from the data taken by and published in [3]. The contour levels of 6 cm image are 3, 5, 15, 25, 35, and 40 $\sigma$, where $1 \sigma = 72 \mu$Jy beam$^{-1}$. On the other hand, contour levels of 3 cm continuum are plotted in 3, 15, 35, 50, 65, and 80 $\sigma$, with $1 \sigma = 66 \mu$Jy beam$^{-1}$. The cross indicates the center of the ring as defined by [3]. The synthesized beam is $2.0'' \times 1.3''$ at 6 cm $1.1'' \times 1.1''$ at 3 cm, and shown at the lower left corner of the respective panels.

saturation levels. As can be seen, NGC 7552 has a galactic bar with radius of $\sim 5$ kpc along with spiral arms emerging from the bar ends.

Forbes et al. (1994)[3] have presented the observation of the center of NGC 7552 in 3 cm and 6 cm continuum (Figure 2). The ring-like structure is completely resolved in both wavelengths. There are several knots in the ring, indicating the regions where the star formation activity is intense.

3. Observation
We observed two molecular lines $^{12}$CO ($J = 2 - 1$) and HCN ($J = 2 - 1$) toward the central region of NGC 7552. $^{12}$CO ($J = 2 - 1$) observation is carried with compact configuration of the Submillimeter Array [4] on 4 August 2006. Seven out of the eight antennas of the SMA were
available during our observation, with baseline lengths ranging from 16 m to 69 m. The data reduction was done by using SMA-specific MIR tasks, which was originally developed for the Owens Valley Radio Observatory [5]. The final integrated intensity and velocity maps have a resolution of 7.0″ × 2.8″ at a position angle (PA) of −11.9°. We do not show the maps of 12CO ($J = 2 − 1$) in this proceeding but the inferred rotation curve. HCN (1 − 0) was observed by the Australian Telescope Compact Array (ATCA) between May and September 2005 in the H75, H168, and H214 configurations, providing baseline lengths ranging from 30 m to 200 m. The data was reduced using MIRIAD. Resolution of finale maps are 2.6″ × 2″ with PA = −80°.

We re-created the 21-cm neutral atomic hydrogen (HI) maps of [6]. By using robust weighting, we obtained higher angular resolution (20″ × 20″) than the images in [6]. The HI maps cover not only the central region but also the outer disk of NGC 7552, which allows us to derive a large scale rotation curve.

4. Results and Discussion

Figure 3 shows the integrated intensity of HCN (1 − 0) emission (grey scale and white contour). The resolution of the HCN (1 − 0) observation is 2.6″ × 2.0″. A ring-like structure is seen, with two knots at the northern and southern ring. The 3 cm continuum shown in §2 is overlaid in contours but now convolved to the same angular resolution as the HCN (1 − 0) map. At this resolution, 3 cm continuum shows two knots in HCN (1 − 0) emission. We therefore confirm that HCN (1 − 0) and 3 cm continuum originate from the same source, i.e. the circumnuclear ring. Note that there are small displacements between the centroids of the dense molecular gas (HCN) and supernova emission (3 cm continuum). We will use these displacements to compute star formation timescale in circumnuclear ring later.

If we assume that the spiral arms in NGC 7552 are trailing, then the radio continuum knots are located downstream of the HCN knots in both NGC 7552. Accordingly, the aforementioned displacements reflects the timescale between the formation of massive stars from dense molecular gas at or close to the contact points, and the eventual demise of these stars as supernova explosions, a schematic explanation of this idea is shown in Figure 6. We then check this argument by calculating the time it would take.

We derived a rotation curve of NGC 7552 based on our measurements of the kinematics of the galaxy in 12CO (from 0 to 1.2 kpc) as well as the HI line (2 to 20 kpc). We fit the sum of two functions to the derived rotation curve. A Brandt curve reflects the gravitational potential of the galactic bulge. An exponential curve reflects the gravitational potential of the galactic disk and dark matter halo. With standard methods (Figure 5) and the widely accepted assumption that the Corotation Radius (CR) is located at the end of the, the pattern speed is therefore derived as 20 km s⁻¹ kpc⁻¹.

The northern radio continuum and HCN knots have deprojected angular offset 0.47″ ± 0.05″, while the offset between southern radio continuum and HCN knots is 0.67″ ± 0.08″. The rotational velocity of the circumnuclear starburst ring is about 170 km s⁻¹, and the pattern speed of the bar about 20 km s⁻¹ kpc⁻¹ (translate to ~10 km s⁻¹ at ring, which has radius of ~0.5 kpc); their net velocity is therefore about 160 km s⁻¹. The propagation time between the northern radio and HCN knots is therefore (3.0 ± 0.4) × 10⁵ years, and that between the southern radio and HCN knots (5.0 ± 0.5) × 10⁵ years.

The timescale is about one order of magnitude shorter than the timescale for OB stars to explode as supernovae. There are two possible reason for the shorter timescale. First of all, the insufficient resolution in 12CO and HI might leads to underestimation in pattern speed and/or overestimation in the rotational velocity of the ring. Besides, star formation in a starburst environment may be top heavy compared to recently accepted Salpeter-like IMF, resulting in a shorter than usual timescale.
Figure 3. Integrated HCN (1 – 0) intensity (left panel) and intensity-weighted mean HCN (1 – 0) velocity (right panel). In the left panel, white contours indicate the intensity of HCN (1 – 0) plotted in 3, 6, 10, 12, and 15 $\sigma$, while $1 \sigma = 0.3$ Jy beam$^{-1}$ km s$^{-1}$. Black contours correspond to the 3 cm continuum image shown in Figure 1 but convolved to the same angular resolution as in HCN (1 – 0). The contour interval is 13% of peak intensity 9.4 mJy beam$^{-1}$. In the right panel, contours correspond to the intensity-weighted mean HCN (1 – 0) velocity just like the color map and are plotted in steps of 20 km s$^{-1}$ starting from -60 km s$^{-1}$ and ending at 60 km s$^{-1}$ with respect to the systemic velocity. A cross is plotted at the center of the galaxy. The synthesized beam is shown at the lower left corner of each panel. The synthesized beam is 2.6$''$ × 2.0$''$ at PA = 80$^\circ$.

Figure 4. Rotation curve derived for NGC 7552 from our $^{12}$CO (2 - 1) maps, plotted as circles, and HI maps, plotted as triangles. We assumed a constant inclination of 25$^\circ$ and position angle for the kinematic major axis of 110$^\circ$. The error bars of rotation curve in central region are ignored in left panel to make the figure neat. Th right panel shows the rotation curve in center region of NGC 7552, along with the uncertainties of data points.
Figure 5. Diagram used to infer the locations of dynamical resonances and pattern speed of a barred galaxy. The angular velocity of the galaxy, $\Omega$, based on an interpolation of the rotation curve shown in Figure 4 is plotted as the black solid line and solid circles. Assuming that CR is at the end of the bar (5 kpc), the pattern speed is therefore the angular velocity $(20 \text{ km s}^{-1} \text{ kpc}^{-1})$ at the bar end. The individual measurements that define the $\Omega - \kappa/2$ (ILR) curve are plotted as asterisks (from $^{12}\text{CO}$ (2 – 1)) and triangles (from HI), where $\kappa$ is the epicyclic frequency of the orbit. The $\Omega - \kappa/4$ (UHR) curve is plotted as diamonds, and the $\Omega + \kappa/2$ (OLR) curve with squares. Resonances occur where the values of these curves are equal to the pattern speed of the bar, assumed to be equal to the rotational velocity at the ends of the bar as indicated by the red horizontal line.

Figure 6. Schematic explanation of the displacement seen in HCN (1 – 0) and 3 cm continuum images.
5. Summary
We have observed the center of NGC 7552 in multiple lines. Both HCN (1 – 0) and 3 cm continuum show ring-like two peaks structures. The displacement between knots of HCN (1 – 0) and 3 cm continuum reflect the star formation timescale between dense molecular gas and supernova explosion. For calculating the timescale, we first derive a rotation curve for the diffuse gas tracer $^{12}\text{CO}$ (2 – 1) and 21 cm Atomic Hydrogen (HI), then derive the pattern speed of bar with standard manner. The pattern speed is 20 km s$^{-1}$ kpc$^{-1}$. After subtracting the pattern speed from the rotational velocity derived from the rotation curve, we estimate the timescale between dense molecular gas and supernova explosion. The timescale is at the shorter end of 5–10 Myr for OB stars to explode as supernovae. This may reflect a top-heavy IMF, or uncertainties in the inferred angular velocities of the ring and bar.

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