Spatially Resolved Star-formation Activity of Starburst Galaxy NGC 253

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ABSTRACT

NGC 253 is well known local starburst galaxy which is currently undergoing a period of intense star formation. We present spatially resolved star-forming activity analysis of NGC 253 using multi-wavelength data from optical to radio. NGC 253 star-forming regions, especially those in the galactic center, are enshrouded by not a few amount of dust produced by their active star-formation. Star-formation tracers which suffer less dust extinction will be essential to investigate the star formation. Paα emission line at 1.875 μm traces actual star-formation activity even at high extinction region that is difficult to measure it in optical wavelengths. We have carried out Paα narrow-band imaging observations which cannot be derived from ground based facilities except for TAO site. Low frequency (e.g. 1.4 GHz) radio continuum data taken with VLA and FIR forbidden lines with *AKARI* FIS/FTS and *Herschel* are also good tracers for current star-formation. Using above data and *AKARI* archive data the differences of star-formation activities among galactic center, bar, bar-end and inter-arm can be revealed.

Keywords: Nearby galaxy, NGC 253, Star-formation, Multi-wavelength

1. OBJECTIVES OF THIS RESEARCH

The objectives of this research is to reveal the sites of star formation using suitable methods; (1) derivation of wide range spectral energy distribution (SED) from NIR to radio for various type of galaxies, (2) we get the information of current star-forming activity (to the star formation history in galaxies) by NIR recombination line and FIR fine structure lines, and (3) radio data leads to physical parameters of molecular gas which is extended around disk.

NGC 253 is a nearby, almost edge-on barred spiral galaxy de Vaucouleurs (1991); the distance is 2.5 Mpc Houghton et al. (1997), which gives a projected linear scale of 12 pc/arcsec. NGC 253 is one of the nearest galaxies showing evidence for a compact nuclear starburst (size ~100 pc, Dudley & Wynn-Williams (1999) which is partially responsible for its high far-infrared luminosity, $L_{\rm FIR} \sim 2 \times 10^{10} L_{\odot}$. Then NGC 253 is very suitable object to research of spatially resolved star formation activity by starburst.

Table 1. Physical parameters of NGC 253

Position	J=2000	00h47m33.13s, -25d17m17.8s
Angular size		27.5 × 6.8 arcsec
Type		starburst
Morphological		SAB(s)c, HII
Flux (mag)	*B* / *V* / *R* / *J* / *H* / *K*	8.04 / 7.07 / 6.66 / 4.81 / 4.09 / 3.77
IRAS (Jy)	12 / 25 / 60 / 100 μm	56 / 155 / 998 / 1681

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2. DATA

In order to investigate and understand star-formation activity from past to current over the galaxy, multi-wavelength observational data should be used. Especially spatially resolved data are important for our purpose.

Table 2. * marked data are showed in this paper.

H recombination line in optical : Hα	Curtis / Schmidt @CTIO *
H recombination line in NIR : Paα	miniTAO / ANIR *
NIR Wide-band : J, H, Ks	miniTAO / ANIR *
MIR Wide-band : 9, 18 μm	*AKARI* / IRC
FIR Wide-band	*IRAS*, *AKARI* / FIS, *Herschel* / SPIRE *
FIR forbidden lines	*AKARI* / FIS-FTS, *Herschel* / PACS *
Sub-mm lines (CO)	NRO, ASTE *
Low frequency 1.4 / 5 GHz	VLA *

The most feature data in this paper is hydrogen recombination line : Paschen-α. Paα at 1.875 μm, the strongest emission line in the near-infrared wavelength range, is less affected by dust thanks to its longer wavelength than the optical lines. Then Paα is a good and direct tracer of dust-enshrouded star-forming regions, and enables us to probe star-formation activity. In order to observe the Paα line, the Atacama NIR camera (ANIR; Konishi et al. 1999) was used. ANIR is one of the instruments for the Cassegrain focus of the University of Tokyo Atacama Observatory 1.0m telescope (miniTAO; Minezakii et al. 2010) which is installed at the summit of Cerro Chajnantor (5640 m above sea level) in the north of Chile. Thanks to the high altitude and extremely low water vapor of the site (Motohara et al. 2010), we can stably observe Paα emission line.

3. MULTI-WAVELENGTH IMAGES OF NGC 253

3.1. Image of Near-Infrared wavelength

Using above images, spatially resolved star-formation activity is revealed. Especially Paα line can see through inside of the galaxy which is extremely obscured by dust. Paα line intensity is stronger than that of Hα in center region of the galaxy (center circle). It shows that star-formation is actually active in galactic center and bar.

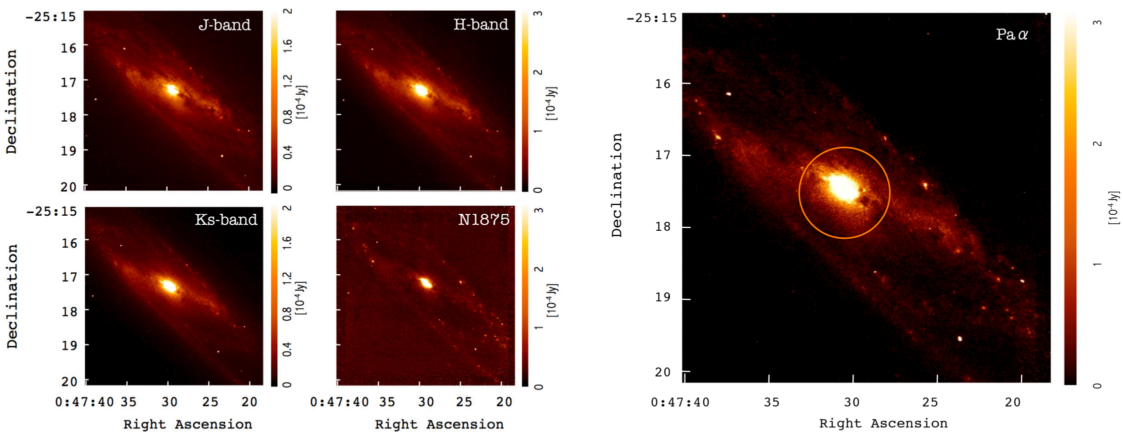

Figure 1. Near-infrared images of NGC 253. Left 4 panels : J, H, Ks and N1875 band images. Right panel : Continuum subtracted Paα image. The continuum is made by interpolation between H and Ks-band.

3.2. Low-frequency and CO Images

The low frequency (cm-wave) radio wave emission from starburst galaxies come from supernovae and supernova remnants synchrotron emission and/or H II region thermal free-free emission. The former (synchrotron) is thought to dominate especially at lower frequency ($1 < \nu < 10$ GHz), and this makes the 1.4 / 5 GHz emission as a good star-formation rate indicator (Condon 1992). Mapping molecular rotational transition line toward starburst galaxies provides distributions, mass, and kinematics of molecular gas, and obtaining more than one lines (e.g., different rotational transitions, isotopologues, spiecies) should provide physical and chemical properties of molecular gas (e.g., temperature, density) which are supposed to regulate starburst activity.

Comparing ^{12}CO(3-2)/(1-0) ratios and star formation efficiencies is a way to investigate relationships between star-formation activity and physical properties of molecular gas. Star formation efficiencies are star formation rate (from 1.4 / 5 GHz radio continuum emissions) per unit molecular gas mass (from ^{12}CO(1-0) intensity). A weak correlation between ^{12}CO(3-2)/(1-0) ratios and star formation efficiencies is seen in the nearby barred spiral galaxy M83 (Muraoka 2007), and it is also seen in NGC 253. There are two possibilities for high ^{12}CO(3-2)/(1-0) ratio (especially at the central region), one is higher fraction of dense molecular gas originate higher star-formation activity, and the other is higher temperature of molecular gas is consequence of higher star formation activity. Observing ^{13}CO(1-0) line in addition to ^{12}CO lines and estimating density and temperature of molecular gas by comparing results from radiative transfer model calculations will be a clue. Muraoka (2007) apply this approach to M83 observation data and find that gas volume densities mainly control ^{12}CO(3-2)/(1-0) ratio rather than gas kinetic temperatures and higher star-formation efficiencies are probably made by higher molecular gas volume densities, and we obtained a consistent result in NGC 253.

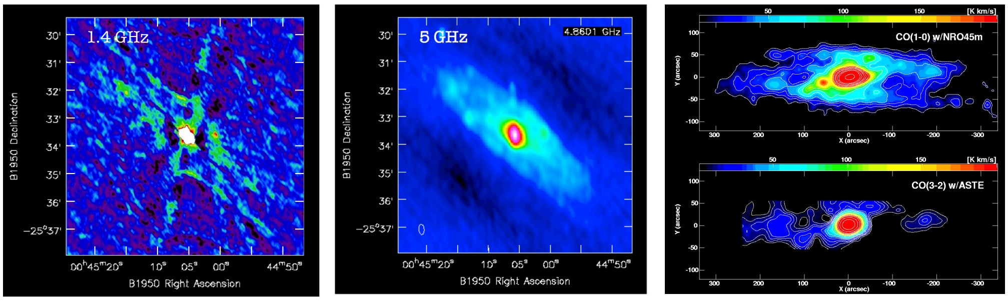

Figure 2. Left panel: 1.4 GHz continuum image taken with VLA. middle panel: 5 GHz continuum image taken with VLA. Right panel: ^{12}CO(1-0) map taken with the Nobeyama 45-m telescope (top) and ^{12}CO(3-2) map take with ASTE telescope (bottom).

3.3. FIR images

Far-infrared emission from galaxies consists of variety of information including thermal dust emission, atomic fine structure lines from cold and warm neutral gas as well as from ionized region. Thermal emission can be a measure of star-forming activity, and the photometric image by SPIRE instrument on *Herschel Space Observatory (HSO)* shows prominent peak in the central region of NGC 253. Compilation of photometric data in middle to far-IR shows the dust emission of most galaxies, including NGC 253, can be modeled well by cold power law and warm grey-body components (Kamenetzky et al. 2014). When compared to the prototypical star-burst galaxy M82, cold dust component is more abundant and warm component is less in NGC 253.

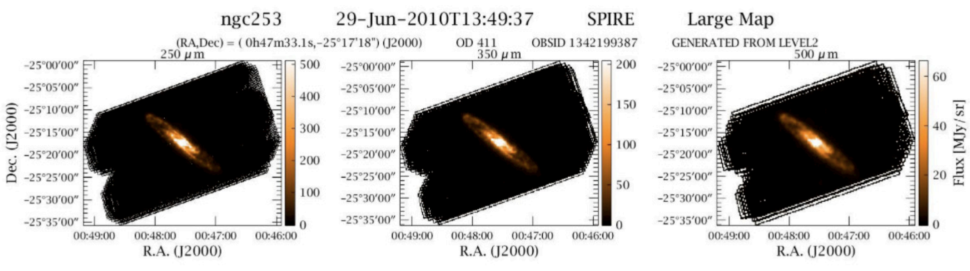

Figure 3. FIR continuum images of NGC 253 by *Herschel* PACS. (http://archives.esac.esa.int/hsa/aio/doc/postcardGallery.html)

SPIRE FTS spectroscopic observation shows many molecular and atomic lines. Analysis of CO high-J (J up to 13) transition lines with low-J observation from ground shows the CO lines are composed of cold and warm components as well (Kamenetzky et al. 2014), and NGC 253 have stronger CO line luminosity compared to M82. With SPIRE and PACS observation, many diagnostic lines can be analyzed, such as [N II]205 and 122 μm, [C II]158 μm, [O I]146 and 63 μm, and [O III]88 and 52 μm lines, as well demonstrated for Seyfert galaxies by Spinogio et al. (2015). From PACS/HSO observation of ionized oxygen lines, [O III]88/52 μm of NGC 253 indicates relatively low density of about 25 electron/cm^3 (Fernández-Ontiveros et al. 2016), indicating that the diffuse ionized component may be dominant. [C II] and [O I] lines are mainly observed from photo-dissociation region (PDR), where [C II]158 μm is the dominant cooling line and [O I] line

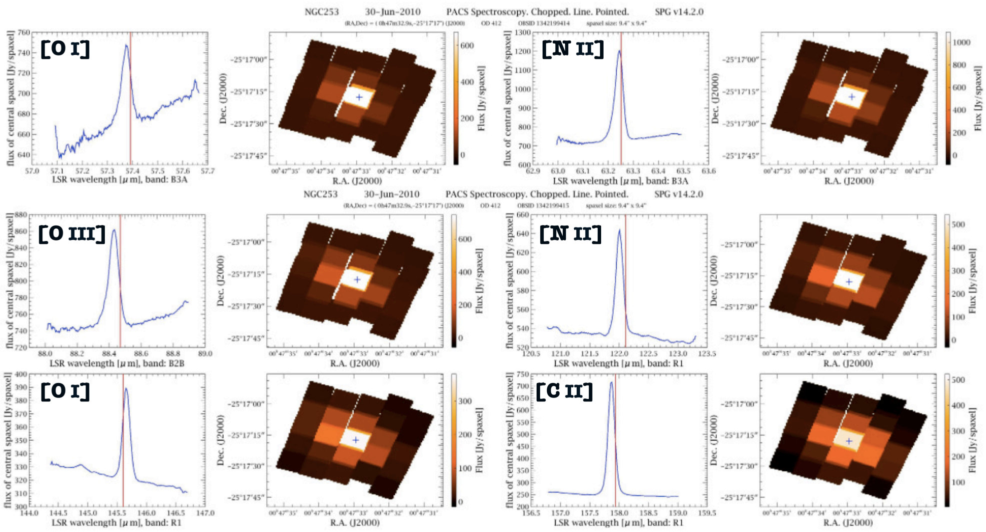

Figure 4. FIR forbidden line images of NGC 253 by *Herschel* SPIRE. (http://archives.esac.esa.int/hsa/aio/doc/postcardGallery.html)

ratio measures the temperature of the PDR. NGC 253 have very strong [C II] and [O I] lines from PDR at temperature several 100 K (Fernández-Ontiveros et al. 2016).

4. STAR-FORMATION OF NGC 253

As you can see the comparison between right 2 figures (left and right figure are mostly equivalent to SFR(Paα) and SFR(IR) respectively), The SFR near GC is more predominant against other regions. Furthermore it seems that the SFR in bar and bar-end is slightly high. There seems to be no difference of the SFR between bar and bar-end. On the other hand the star-formation is not active in the arm region.

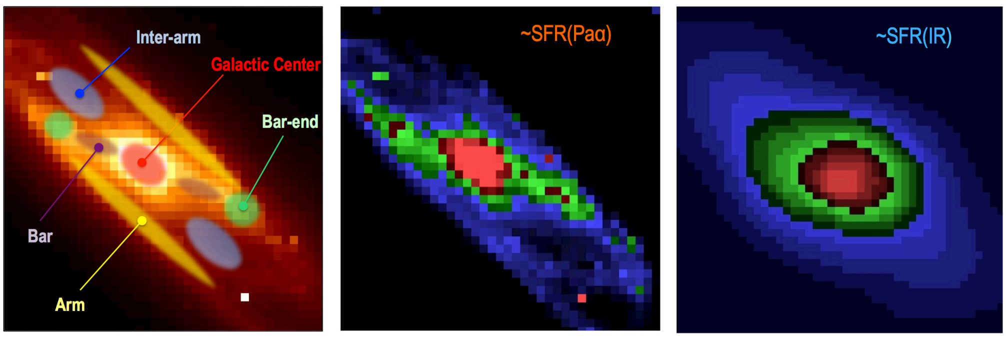

Figure 5. Left : It divides the galaxy into several areas (Galactic center, Bar, Bar-end, Arm and Inter-arm) and considers the star formation rate. Center & Right : Contours of Paα (center) and IR luminosity.

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