A Sub-arcsecond Study of Ionized Gas in NGC 253

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Abstract.
The nuclear region of the starburst galaxy NGC 253 was observed in H92α (8.3 GHz) and H75α (15.4 GHz) recombination lines at sub-arcsecond resolution using the A-configuration of the Very Large Array (VLA). In the highest resolution observations at 15.3 GHz, we have detected a compact (< 5 pc), high density ($> 5 \times 10^4$ cm^{-3}) ionized region which is nearly coincident with the radio continuum peak near the nucleus. Modeling of RRL emission from this region shows that about 1000 O stars are needed to maintain the ionization. Assuming the Salpeter initial mass function, the implied overall stellar density corresponds to that of a super star cluster.

1. Introduction

Ionized gas in the nuclear region of the prototypical starburst galaxy NGC 253 has been studied at arcsecond resolutions at optical (Arnaboldi et al 1995, Prada, Gutierrez, & McKeith 1998), infrared (Engelbracht et al 1998, Boker, Krabbe, & Storey 1998, Keto et al 1999) and radio (Anantharamaiah & Goss 1996) wavelengths. These studies have revealed the presence of large quantities of ionized gas in the central 100 pc region with complex spatial and kinematic structures. Radio continuum observations at sub-arcsecond resolution (Ulvestad & Antonucci 1997) have shown a number of compact sources within the central 15″ region including a bright source near the possible nucleus. High resolution optical observations with the Hubble Space Telescope have discovered four super star clusters (SSCs) in the central region (Watson et al 1996). None of the SSCs have a positional correspondence with the radio continuum peaks. The brightest peak observed in mid-infrared images at arcsecond resolution (Boker et al 1998, Keto et al 1999) is also not coincident with the central compact radio source but is offset by about 2.5″ to the southeast. The 12.8 μm [Ne II] emission peak at this offset position has been interpreted by Keto et al (1999) as ionized gas excited by OB stars of one of the SSCs discovered by Watson et al (1996). SSCs, which have been found in many starburst regions (Meurer et al 1995) are believed to be progenitors of the present day globular clusters.
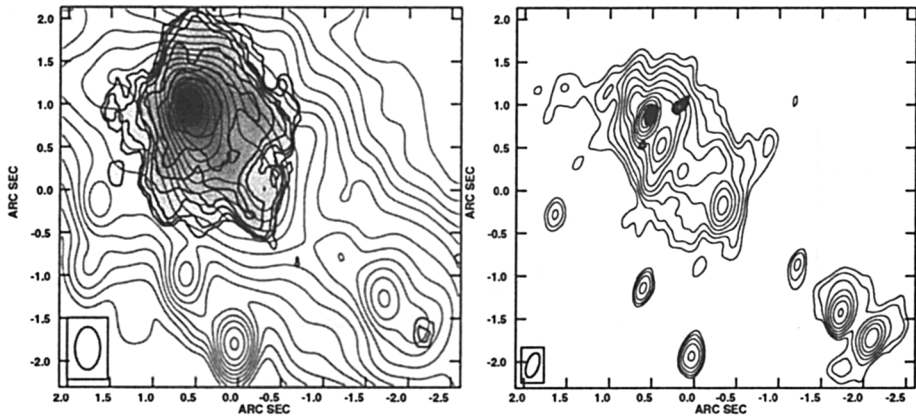
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Figure 1. Radio Continuum (thin contours) and velocity-integrated recombination line emission (thick contours and grey scale) at 3.6 cm (*left*) and 2 cm (*right*). The beams, shown as insets, are $0.5'' \times 0.3''$, PA $= 0°$ at 3.6 cm and $0.3'' \times 0.15''$, PA $= -20°$ at 2 cm. The first continuum contour level at 3.6 cm is 0.75 mJy/beam and increases by a factor of 1.3. For the H92α line, the first contour is 20 Jy/beam m s^{-1} and increases by a factor 1.4. At 2cm, the first continuum contour is 0.5 mJy/beam and the first line contour is 80 Jy/beam m s^{-1}. Both increase by a factor 1.5

In this paper, we present the first sub-arcsecond imaging of ionized gas in the nuclear region of NGC 253. The VLA was used in its A-configuration to observe the H92α (8.3 GHz) and H75α (15.3 GHz) radio recombination lines (RRLs) with angular resolutions of $0.5'' \times 0.3''$ (PA $= 0°$) and $0.3'' \times 0.15''$ (PA$=$ -20°) respectively. At the distance of 3 Mpc to NGC 253, $1''$ corresponds to a linear size of 16 pc. Since RRLs do not suffer from extinction, these observations are able to probe the ionized gas in the very central regions and have provided evidence for a possible SSC coincident with the central radio continuum peak.

2. Observations and Results

Observations were made in the largest (A) configuration of the VLA which has interferometric baselines ranging from 0.7 - 36.4 km. For the H92α observations near 8.3 GHz, a bandwidth of 25 MHz and 31 spectral channels were used. The velocity resolution after hanning smoothing was 56 km s^{-1}. For the H75α line at 15.3 GHz, 15 spectral channels over a bandwidth of 50 MHz with a resolution of 123 km s^{-1} was used. At both frequencies data was taken over two 8 hour sessions. Amplitude, phase and bandpass calibrations were made using standard methods. The continuum data was self calibrated and the solutions were applied to the line data. Natural weighting was applied to the visibilities to make the final continuum and line images. The rms noise in the line images were 80 μJy/beam and 260 μJy/beam for the H92α and H75α lines respectively.
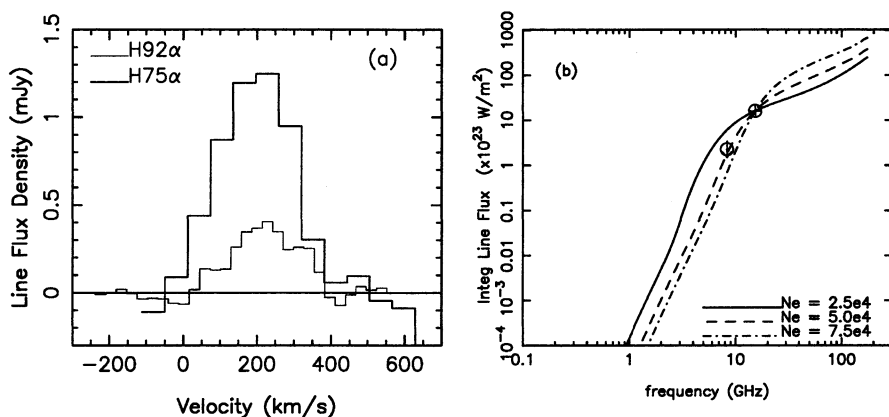
Figure 2.   *(a)* Recombination line profiles at 8.3 GHz and 15.3 GHz at the position of the continuum peak at 2 cm. *(b)* Model of RRL emission from a collection of HII regions at three different densities.

Fig 1 shows the line and continuum images of the central $5''$ region. The continuum images at 3.6 cm and 2 cm show compact structures which are consistent with the results obtained by Ulvestad & Antonucci (1997). The grey scale with thick contours, superposed on the two continuum images, indicates the regions where RRL emission was observed. The H92α line emission is sharply peaked at $\sim 0.8''$ south of the continuum peak and extends over a region of $\sim 2.5''$ (40 pc). The peak line emission is 1.2 mJy/beam. Another weak compact line emission region is observed near a continuum peak in the southwest region along the major axis. The higher frequency H75α line emission (Fig 1b) shows only two compact peaks near the central region. The brighter line emission is nearly coincident (offset $\sim 0.1''$) with the continuum peak at 2 cm. The peak line emission is 1.5 mJy/beam. In the high resolution observations at 2 cm any possible extended H75α emission would be resolved out.

3.   Does the Ionized Gas Indicate a Super Star Cluster?

In this short paper, we focus on the interesting implications of detecting a compact H75α line emission region close to the radio continuum peak at 2 cm. Fig 2a shows the H75α line profile at the continuum peak ($[\alpha, \delta]_{1950} = 00^h 49^m 5.793^s$, $-25°33'39.06''$) over one beam area ($0.3'' \times 0.15''$) corresponding to a linear size of $\sim$ 5 pc x 2.5 pc. The H92α line profile at this position (shown in the same Fig) corresponds to a larger beam area ($0.5'' \times 0.3''$) and hence can be regarded as an upper limit to the H92α line emission over the 5 pc x 2.5 pc region. The velocity-integrated flux densities of the two lines in Fig 2a are 16.1 $\times 10^{-23}$ W m^{-2} and 2.3 $\times 10^{-23}$ W m^{-2} respectively. Using these line strengths and also the observed continuum flux densities, we obtain constraints on the properties of the ionized gas in the central 5 pc x 2.5 pc region.

Following the procedure described in Anantharamaiah et al (2000), the observed RRL emission is modeled as arising from a collection of N HII regions

characterized by density n_e, temperature T_e (assumed here to be 10,000K) and size l. Acceptable models are those which are consistent with the observed H75α line, the upper limit to the H92α line and the continuum flux densities at 8.3 GHz, 15.2 GHz and 22.3 GHz, which we estimate to be 55, 41, and 30 mJy, respectively, using the high resolution images by Ulvestad & Antonucci (1997). Fig 2b displays three models with different densities and shows that, to be consistent with the H92α line, only densities above 5×10^4 cm^{-3} are allowed.

The model that fits the data shows that within the 5 pc x 2.5 pc region there are 35 HII regions, each of density 7.5×10^4 cm^{-3} and size 0.25 pc. The volume filling factor of the ionized gas is 0.02 and the total mass is 530 M$_\odot$. The required Lyman continuum photon production rate, N_{Lyc}, is 1.2×10^{52} s^{-1}. Adopting the stellar atmosphere model of Vacca, Garmany, & Shull (1996), this value of N_{Lyc} corresponds to a total number of $\sim 10^3$ O stars, assuming the Salpeter initial mass function and a stellar mass range of 1 to 80 M$_\odot$. The corresponding total stellar mass is $\sim 2 \times 10^5$ M$_\odot$ and the number of stars with M > 1 M$_\odot$ is 7×10^4 and about 10^6 stars with M > 0.1 M$_\odot$. This high density of stars confined to a 5 pc x 2.5 pc region correspond to that of a SSC (Meurer et al 1995). In NGC 253, four SSCs have been discovered in the nuclear region (Watson et al 1996) using HST observations. However, none of these are coincident with the radio continuum peaks. The detection of RRLs at sub-arcsecond resolution do indicate the possibility of an SSC near the central radio continuum peak which may be totally obscured at optical and infrared wavelengths.

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