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NEW RESULTS FROM H92α RECOMBINATION LINE OBSERVATIONS OF NGC 253

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RESUMEN

Observaciones de la región nuclear de NGC 253, en la línea de recombinación H92α y con una resolución de 1''8 × 1''0, muestran (1) similaridades en las estructuras delineadas por las emisiones en la línea y en el contínuo, y (2) a un patrón de velocidades en forma de "s", interpretado como 3 diferentes componentes de rotación —de cuerpo rígido en el mismo sentido que el resto de la galaxia, rotación con el doble de velocidad alrededor del eje menor y contra-rotación en el núcleo. Un modelo simple da una masa de gas ionizado de $\sim 5 \times 10^5$ $M_\odot$y una masa dinámica de $\sim 3 \times 10^8$ $M_\odot$dentro de un radio de 5''. La producción de fotones UV es de al menos $N_{Lyc} \sim 10^{53}$ s^{-1}. La cinemática peculiar del núcleo de NGC 253 indica una barra secundaria cerca del centro o un evento de fusión o acreción durante la historia de la galaxia.

ABSTRACT

Observations of the H92α recombination line with an angular resolution of 1''8 × 1''0 in the nuclear region of NGC 253 reveal (1) similar spatial structures in the line and continuum emissions, which we attribute to the similarity in the distribution of thermal and non-thermal gases and to the amplification of the non-thermal radiation by stimulated line emission and (2) a systematic S-shaped velocity pattern which we interpret as evidence for 3 distinct rotations in the central region —solid-body rotation in the same sense as the outer galaxy, rotation about the minor axis with almost twice the speed, and finally a counter-rotating inner core. A simple but not unique model for the H92α emission gives a mass of $\sim 5 \times 10^5$ $M_\odot$for the ionized gas whereas the dynamical mass within a radius of 5'' is $\sim 3 \times 10^8$ $M_\odot$. The minimum rate of production of UV photons is $N_{Lyc} \sim 10^{53}$ s^{-1}. The unique nuclear kinematics in NGC 253 may be indicative of a secondary bar near the centre or an accretion or a merger event during the history of the galaxy.

Key words: **GALAXIES: INDIVIDUAL: NGC 253 — GALAXIES: ISM — RADIO LINES: GALAXIES**

1. INTRODUCTION

The velocity field in the nuclear starburst region of the Sc galaxy NGC 253, located in the Sculptor group, has been studied in the optical, IR, and radio bands (see Puxley & Brand 1995). The measured Hα radial velocities along various position angles near the nucleus show that, in addition to solid body rotation in the central region, there are large non-circular motions. The exact nature of these motions is uncertain due to problems of obscuration (Canzian et al. 1988). Radio recombination lines (RRL), which do not suffer from obscuration, provides an alternative method of studying the kinematics and conditions of the ionized gas in the nuclear region. NGC 253 is a relatively strong RRL source with a peak H92α (ν_{rest} = 8.309 GHz) line flux density of about 8 mJy, with most of the line emission arising in the nuclear region. Here we present some results from new observations of this line.

2. OBSERVATIONS AND RESULTS

We have observed the H92α line using the B, C, and D configurations of the VLA for a total duration of $\sim$ 40 hours. The resulting angular resolution is 1''8 × 1''0 (PA = 10°) and the rms noise in individual channels is $\sim$60 μJy/beam. We used 32 spectral channels with a velocity resolution of 56.4 km s^{-1}and a velocity coverage of $\sim$ 850 km s^{-1}centered at V_{Hel} = 200 km s^{-1}. The continuum image of the central region is shown in Fig. 1a. The H92α line emission from the same region, integrated over velocity, is shown in Fig. 1b. The distribution

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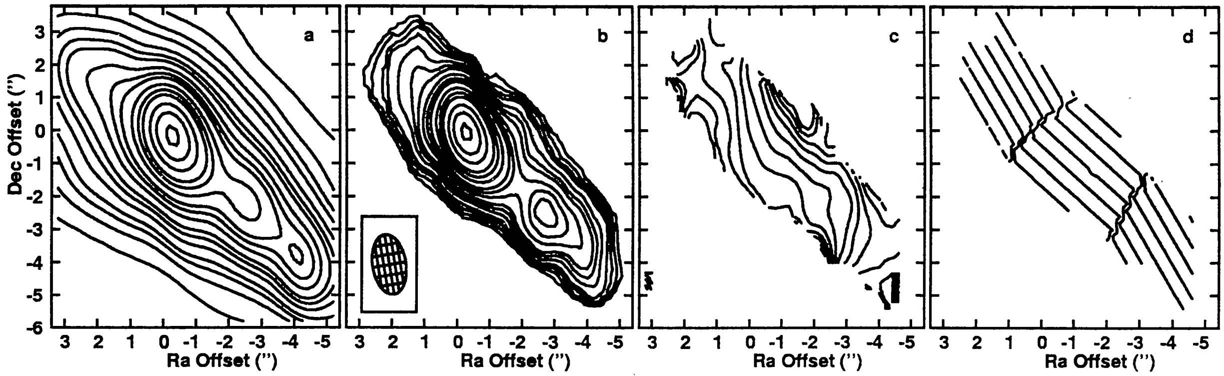

Fig. 1. NGC 253: (a) Continuum at 8.3 GHz. The first contour is 0.204 mJy/beam and the intervals double at contours 4, 7, 10 and 13. (b) Integrated H92α line. The first contour is 7.1 Jy/beam m s^{-1} and intervals are same as in (a). (c) Observed Velocity field and (d) Model Velocity field. Contours are 170 to 270 km s^{-1} in steps of 10 km s^{-1}. The lowest contour is to the south-east. The offsets are from 00^h 45^m 5.80^s, $-25°33'39.1''$ (B1950).

of central velocities obtained by fitting a Gaussian profile at each pixel is shown in Fig. 1c. The mean width of the lines (FWHM) is about 200 km s^{-1} and the central velocity of the integrated line profile is 220 km s^{-1}.

3. SPATIAL STRUCTURE OF LINE EMISSION

The similarity of the spatial structures of continuum and line emission seen in Figs. 1a,b could be due to either or both of the following. 1) The line emission may be dominated by stimulated emission in which the background non-thermal radiation is amplified by a foreground ionized screen. This scenario requires ionized gas densities of $< 10^3$ cm^{-3}. For $T_e = 5 \times 10^3$ K, the deduced emission measures and total masses are, respectively, $\sim 1.5 \times 10^6$ pc cm^{-6} and 3×10^5 $M_\odot$ for $n_e = 10^3$cm^{-3} and $\sim 9 \times 10^5$ pc cm^{-6} and 3.5×10^6 $M_\odot$ for $n_e = 50$ cm^{-3}. The corresponding Lyman continuum photon rate is $N_{Lyc} \sim 1 - 1.5 \times 10^{53}$ s^{-1}. 2) The second possibility is that the ionized gas in the central region (presumably a collection of H II regions) is also distributed as the non-thermal emitting gas (possibly a collection of SN remnants), and the peaks of continuum and line emission represent centres of starburst activity. In these models, the electron density is high (> 500cm^{-3}) and the line emission is dominated by internal stimulated emission in the higher density models. In the lower density models, stimulated emission due to the background non-thermal emission is a major effect as in the case of a foreground screen. If the H II regions sizes are ~ 0.5 pc, $T_e = 5000$ K and $n_e = 500$ cm^{-3} then, to explain the line emission, $\sim 5 \times 10^5$ H II regions are required, corresponding to a total mass of 4.2×10^5 $M_\odot$ and $N_{Lyc} = 1.1 \times 10^{53}$ s^{-1}. If the density is increased to 10^4 cm^{-3} then 1400 H II regions are required, with a total mass of 2.3×10^4 $M_\odot$ and $N_{Lyc} = 1.2 \times 10^{53}$ s^{-1}. The spatial structure of line to continuum ratio (i.e., the ratio of Figs. 1b and 1a) is also similar to the continuum emission (Fig. 1a) implying that a simple uniform screen model with a constant amplification factor cannot explain the observations. This similarity implies that the ionized gas does have the same spatial structure as the non-thermal continuum emitting gas. Clearly, this can occur if the peaks in the continuum (and line) distribution represent centres of starburst activity. While both models can explain the observations of the H92α line, none of them can satisfactorily account for the observations of RRLs at other frequencies (e.g., at 20 cm and 3 mm). A combination of both high ($> 10^3$cm^{-3}) and low (< 100 cm^{-3}) density gas may be required to explain all the observations.

4. KINEMATICS OF THE IONIZED GAS

An unusual aspect of the velocities shown in Fig. 1c is that the iso-velocity contours in the nuclear region run roughly parallel to the major axis and they have an overall stretched **S** shape. For solid-body rotation in the plane of the galaxy, as is usual in the central regions, the iso-velocity contours are expected to run parallel to the minor axis. Fig. 2a shows the central velocities along the major and minor axes obtained from the Gaussian fits. Figs. 2b,c compare the H92α velocity along the major axis with those measured in Hα and [N II] (Ulrich 1978; Muñoz-Tuñon et al. 1993), CO (Canzian et al. 1988) and Brγ (Puxley & Brand 1995). In the region of overlap, the mean H92α velocity and the velocity gradient are most consistent with the CO and Brγ data and less consistent with the optical data. The inconsistency between optical and longer wavelength measurements

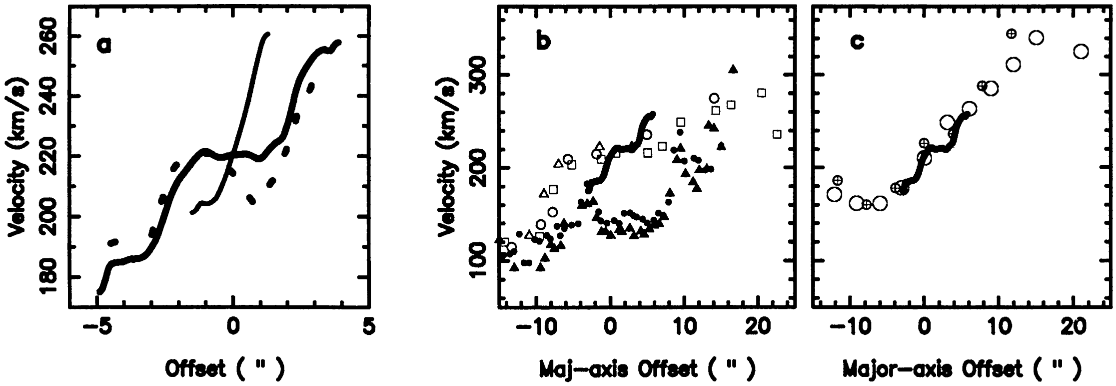

Fig. 2. (a) H92α Velocity along major-axis (*thick line*), minor-axis (*thin line*) and along major-axis with higher angular resolution (*dotted line*). (b) Comparison of H92α velocity (*solid line*) with that of Hα and [N II]; *open symbols* —data from Ulrich (1978), *filled symbols* —data from Muñoz-Tuñon et al. (1992). (c) Comparison of H92α velocity with that of CO (Canzian et al. 1988) (*open circles*) and Brγ (Puxley & Brand 1995). The offsets are from 00^h 45^m $5.68^s, -25°33'40.3''$ (B1950).

must be due to extinction, as noted by Canzian et al. (1988) and Puxely & Brand (1995). The agreement in velocity between H92α , CO and Brγ indicates that the ionized gas observed in H92α is located in the nuclear region. Velocity gradients of ~11 km s^{-1}per arcsec along the major axis and ~18 km s^{-1}per arcsec along the minor axis could be interpreted as rotations about the minor and major axes respectively. The solid curve in Fig. 2a shows that the velocity along the major axis does not represent a simple gradient. The dashed curve in Fig. 2a, which has a slightly higher angular resolution (1$''$.6 × 0$''$.9) obtained using only the B-configuration data, shows that the sense of the velocity gradient actually reverses in the central 2$''$region. This reversal of the velocity gradient indicates possible counter-rotation in the central region. We fitted a rotation model to the observed velocity field shown in Fig. 1c (see Anantharamaiah & Goss 1996). The model has 3 nested rings or disks of ionized gas rotating like solid bodies. The outermost ring with a velocity gradient of 12 km s^{-1}per arcsec rotates in the plane of the galaxy and is likely to be a part of the general solid-body rotation found near the center on larger scales (Pence 1981; Canzian et al. 1988; Puxley & Brand 1995). The second ring, which is interior to the outer disk dominates the velocity field in the central region with a gradient of 24 km s^{-1}per arcsec and it is oriented perpendicular to the outer disk, i.e., along the minor axis of the galaxy. It should be noted that the data only implies that the spin axis of the second ring lies in the plane of the galaxy and need not necessarily be aligned with the projected major axis of the outer disk. The third and innermost disk, the evidence for which is tentative, is in the plane of the galaxy and appears to be rotating counter to the outermost disk. The model velocity field obtained with all 3 rotations, Fig. 1d, roughly mimics the observed velocity field shown in Fig. 1c. The velocity gradient of the inner most disk is ~8 km s^{-1}per arcsec. The highest gradient, 24 km s^{-1}per arc-second, observed for the minor-axis rotation implies, with circular rotation, a dynamical mass of ~ $3 \times 10^8 M_\odot$within 80 pc from the nucleus. The fitted model indicates that the dynamical centre is ~ 1.8$''$ south-west of the continuum peak in Fig. 1a. If we consider these 3 components as a kinematic sub-system, which is distinct from the main disk, then it may be a signature of a merger or an accretion event during the history of the galaxy (Hernquist & Barns 1991). On the other hand it may be possible to explain the velocity field as due to motion in a bar potential. However, since the position angle of the known bar in NGC 253 is ~ 68°(Scoville et al. 1985) and the iso-velocity contours in Fig. 1c run parallel at a PA of ~51°, the velocity field may be indicative of an interior secondary bar aligned along the major axis.

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