Sub-arcsecond imaging of the radio continuum and HI absorption in the Medusa Merger

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Abstract. We present new MERLIN observations of both the radio continuum and neutral hydrogen absorption against NGC 4194, "the Medusa Merger". These observations are the highest angular resolution observations, made to date, of the neutral gas within this source. In presenting this new data we discuss the nuclear radio continuum structure of this very efficient starburst galaxy, as well as a further investigation of the dynamics and distribution of HI in the galaxy's nucleus. We conclude by placing these results into the context of other observations of this source, for example high resolution observations of CO emission, with the intention of further understanding the cold neutral and molecular ISM of this source; the fuel for the ongoing starburst.

INTRODUCTION

The Medusa merger (NGC 4194) is a nearby (D=39 Mpc) star-forming galaxy of intermediate infrared luminosity ($L_{\rm fir} = 8.5 \times 10^{10}\,L_{\odot}$). This source falls into a luminosity class, considerably lower than the well-studied ultra-luminous infrared galaxies (ULIRGs) however it still shows evidence for areas of intense starburst activity [1, 2, 3]. The optical morphology of the Medusa merger, as its name suggests, traces clumpy and extended features which stretch $\sim 1'$ to the north of the main optical nucleus. These 'hair-like' extensions, indicative of tidal tail features resultant from the galaxy's ongoing merging event, contain significant volumes of molecular gas [4] although no indications of ongoing star-formation in the tidal tail have been detected as yet [1]. The majority of star-formation in the Medusa merger is concentrated in the extended nuclear starburst. This central region contains large volumes of molecular gas [5] and dust, as well as hosting the majority of the ongoing star-formation. This extended nuclear region appears have a high star-formation efficiency [5].

In these proceedings we present sub-arcsecond resolution observations of the 1.4 GHz radio continuum emission, tracing the starburst activity, and neutral hydrogen (HI) absorption against this region.

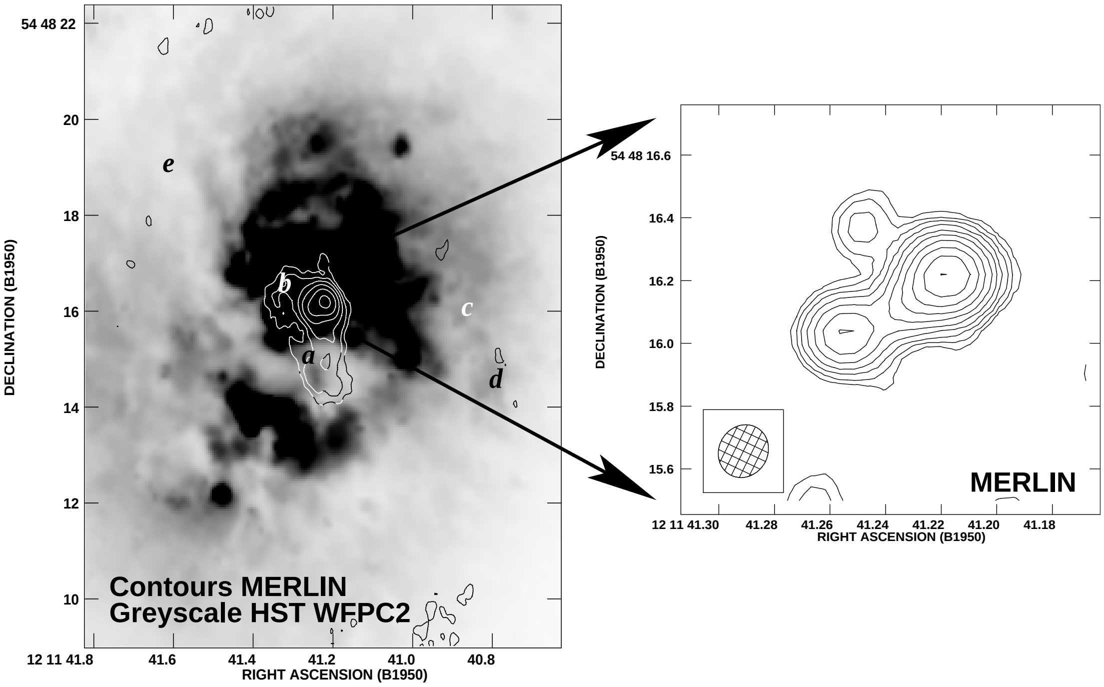

FIGURE 1. Overlay of a *uv*-tapered (800 kλ) 1.4 GHz radio continuum emission in contours over a grey-scaled F606W WFPC2 *HST* image. The contour levels of the radio image are -1, 1, 2, 4, 16, and 32 times 0.3 mJy bm^{-1}. The astrometrical error in the alignment of these two images is estimated to be $\sim$100 mas. Labels *a, b, c, d* and *e* indicate the positions of the ^{12}CO peaks as observed by [5]. The inset image shows a contour map of the brightest two radio components imaged with uniform weighting. The restoring beam of this inset image is $0\farcs170\times0\farcs151$ and the contours are $\sqrt{2}$ times 0.35 mJy beam^{-1}.

OBSERVATIONS

We have used the UK's Multi-Element Radio Linked Interferometric Network (MERLIN) [6] to observe both the 1.4 GHz radio continuum and neutral hydrogen (HI) absorption structure of the central few hundred parsecs of NGC 4194 at sub-arcsec angular resolutions. On 2003 March 15 NGC 4194 was observed using MERLIN at 1408.66 MHz for 18 h with regularly interspersed observations of the phase calibrator 1205+545. Throughout the observations dual hands of circular polarisation were recorded across an 8-MHz bandwidth which were correlated into 64 spectral channels resulting in a velocity resolution of $\sim$26 km s^{-1} channel^{-1}. These interferometric data were calibrated in a standard fashion within local MERLIN software and NRAO's Astronomical Image Processing Software (AIPS). This constitutes the highest angular resolution study made to date of both the radio continuum and neutral gas structure in this merger galaxy.

THE RADIO CONTINUUM STRUCTURE

The contour images in Figs. 1 and 2 both show the *uv*-tapered 1.4 GHz radio continuum structure of the central kiloparsec region of the Medsua merger. This MERLIN image,

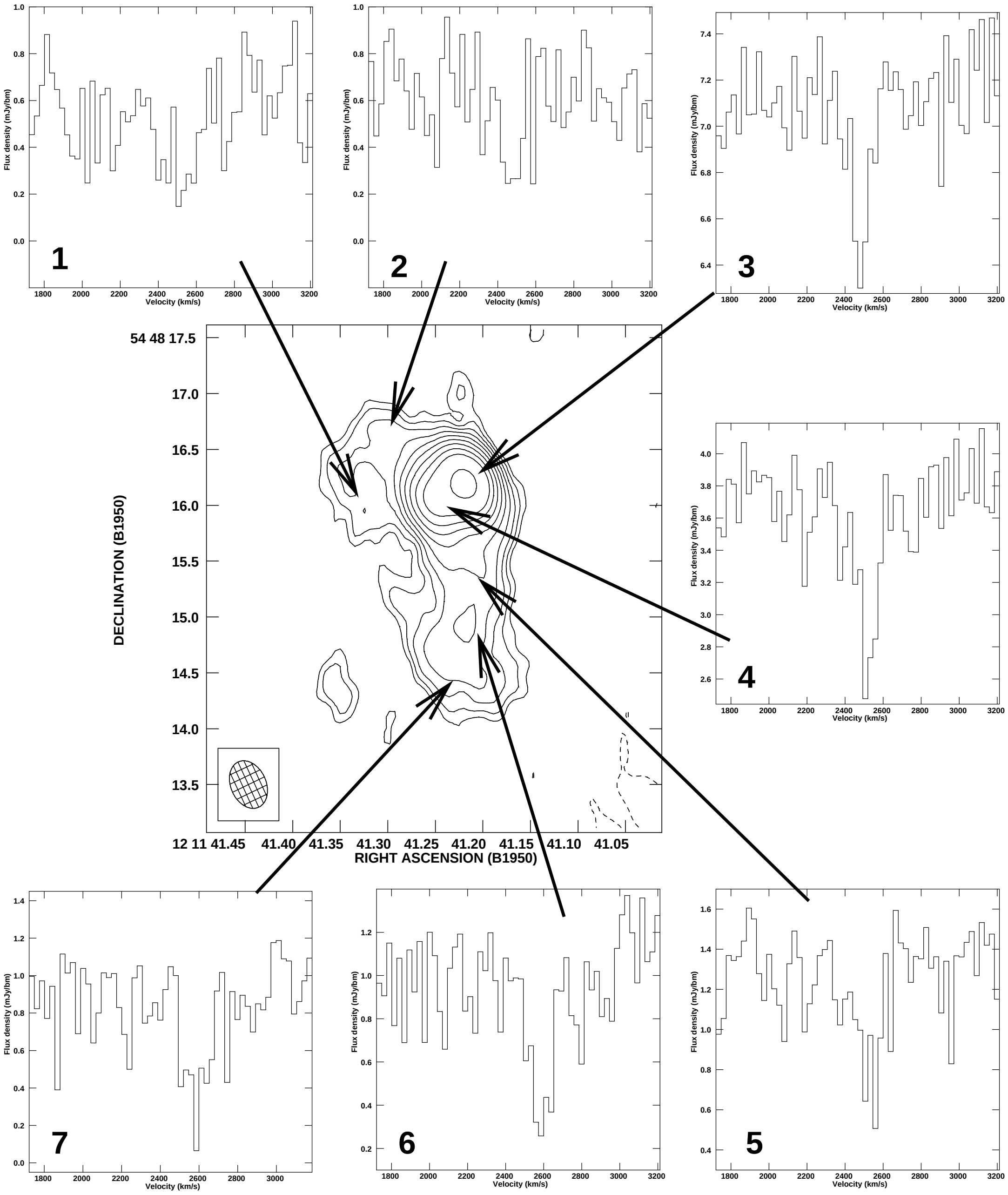

FIGURE 2. Montage of the $800\,\mathrm{k}\lambda$ *uv*-tapered radio continuum structure with selected H I absorption spectra. The contour levels are $\sqrt{2}$ times $0.3\,\mathrm{mJy\,bm^{-1}}$ and the image is convolved with a $0\farcs45\times0\farcs32$ restoring beam.

with an angular resolution of $\sim0\farcs35$, shows the strong emission toward the northern 'nuclear' region of the source along with a more diffuse 'skirt' of radio emission south of this bright northern core. The 'nuclear' components (area of brightest radio emission toward the north of these images) is only partially resolved in Figs. 1 and 2. When imaged at the full resolution of MERLIN ($\sim0\farcs1$ at 1.4 GHz; see Fig. 1 *inset image*) this

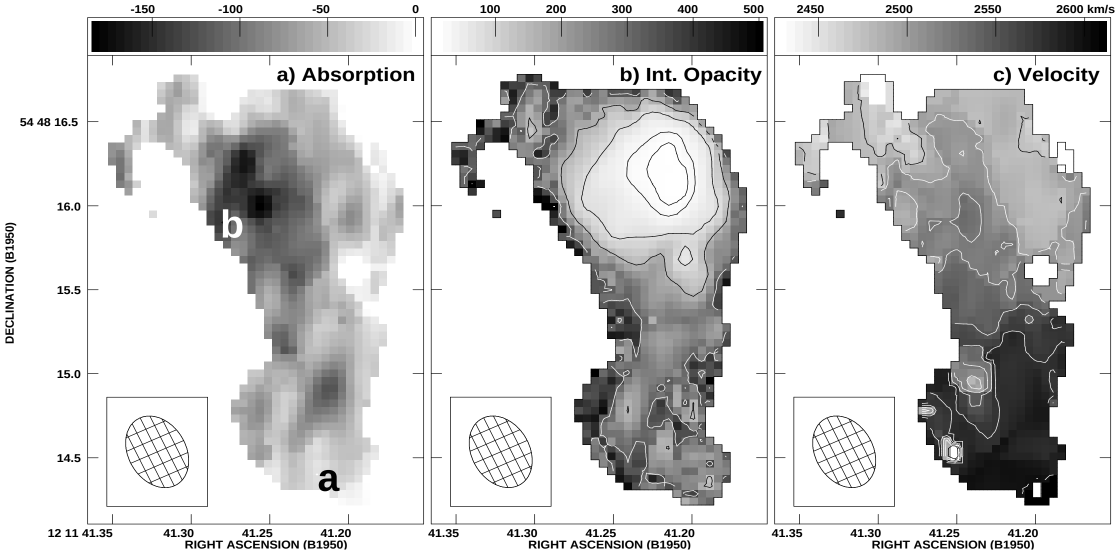

FIGURE 3. **a)** The leftmost image shows the integrated absorption signal across the centre of the Medusa merger. Note the absorption shown is dependent on the strength of the continuum emission. The two symbols (a and b) shown on the left-most image represent two of the CO emission peaks from [5]. **b)** The central image shows the Gaussian fitted, integrated optical depth ($\int \tau$dV) across the same region as **a**. It should be noted that errors in this image increase in areas where the radio continuum flux density is at a minimum. This image has been blanked in areas where the radio continuum is less than 0.6 mJy beam^{-1}. **c)** The righthand map represents the HI absorption velocity field over areas were significant radio continuum and absorption line signal were detected.

component is clearly resolved into two compact radio components separated by $0.''35$ ($\sim$65 pc), a more detailed analysis will be presented in Beswick et al., (*in prep*). These two compact components are both unresolved in our highest resolution MERLIN images (<25 pc). These two components structurally resemble a weak 'Seyfert-like' nuclei, see for example [7, 8, 9]. However, their radio luminosity is low ($\sim 10^{20}$ W Hz^{-1}) and we are able to also place enclosed dymanical mass limits on this region (see below) both of which preclude the exisance of a large mass AGN component and are more consistent with the radio emission arising from the starburst.

THE GAS

Strong ($\tau = 0.1 \rightarrow 1.4$) HI absorption has been detected against all of the significant 1.4 GHz radio emission imaged with MERLIN (see Fig. 2 and 3). The distribution and velocity structure of HI absorption is resolved by these MERLIN observations (Fig. 3).

The HI absorption detected against the radio continuum structure of NGC 4194 shows significant variations in the observed opacity and column density. Against the brightest radio components, toward the north of the source, the derived HI columns are 0.08×10^{19}T$_{\rm spin}$ atoms cm^{-2}, compared to $5\rightarrow10\times10^{19}T_{\rm spin}$ atoms cm^{-2} against the southern skirt of radio emission. This significant increase in HI column density is spatially consistent with the position of the dense, obscuring dust lane observed at optical wavelengths (see Fig. 1). Additionally it is found that the areas of highest H I columns are coincident with the spatial distribution of the peaks in ^{12}CO [5]. The velocity structure observed in these H I absorption observations is consistent with the lower resolution CO observations of [5]. The spatial coincidence of the H I, CO peaks and the dust lanes, and the consistency of the velocity structures observed in the cold gas, imply that these components of the ISM are all probably physically associated.

The velocity structure of the H I absorbing gas observed against the radio continuum in the Medusa (see Fig 3**c**) globally shows a North to South velocity gradient that is consistent with the velocities and dynamical structures observed at lower resolution in CO [5]. This north-south velocity gradient is equivalent to $\sim$60 km s^{-1} arcsec^{-1} ($\sim$320 km s^{-1} kpc^{-1}). This gradient extends across the entire area where absorption is detected ($\sim$0.5 kpc) providing a limit of $\sim 10^6$ M$_\odot$ of enclosed mass, assuming that the gas is undergoing circular motion. This low limit on the enclosed mass constrains the size of any supermassive black-hole within the centre of this galaxy.

CONCLUSIONS

We have used MERLIN to image both the 1.4 GHz radio continuum emission and neutral hydrogen absorption against this radio background continuum at sub-arcsecond angular resolutions. Consequently these observations have, for the first time, traced the neutral gas kinematics in the Medusa on linear scales of $<$50 pc.

The sub-arsecond, 1.4 GHz radio continuum structure of the central kiloparsec of the NGC 4194 shows multiple weak radio components. The two most compact and luminous of these components are situated toward the north of the radio continuum structure and morphologically resemble the nucleus and jet structure of nearby low powered Seyfert nuclei. However the low radio luminosity and dynamical mass estimates for the central region imply that these components are probably more consistent with the radio emission from the starburst itself.

Across the entire radio continuum structure of the centre of the Medusa merger high optical depth H I absorption has been detected. This H I column densities of this absorption is inhomogeneously distributed with significantly higher H I opacities detected toward the south of the radio emission. These areas of high H I column densities are shown to spatially coincide with the distribution of obscuring material observed in optical images of this galaxy, as well as, along the same lines-of-sight as the areas of larges CO emission. Consequently it is concluded that all three of these components of the cold ISM are probably spatially associated.

The neutral gas kinematics as observed with these H I absorption observation show a consistent those of the molecular gas. These observations trace a distinct north to south velocity gradient in the H I absorption that is traced over $\sim$ 0.5 kpc of the nuclear region (limited by the extent of the background radio continuum). This velocity gradient, if assumed to be tracing gas in approximately circular motion across the 0.5 kpc region imaged, implies an enclosed mass limit of $\sim 10^6$ M$_\odot$.

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