# Molecular Outflow in the AGN/Starburst Galaxy NGC 6764

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## ABSTRACT

NGC 6764 is a composite galaxy exhibiting central activity (LINER) and recent massive star formation (Wolf-Rayet galaxies). We present new high-resolution interferometric data of the CO(1-0) and CO(2-1)emission in the central part of the galaxies together with high resolution VLA data of the radiocontinuum emission at 20 and 3.5 cm. The nucleus shows a carateristic bubble-like radiocontinuum emission. The total molecular gas in the center is found to be about 7x10$^8$ M$_\odot$, with a CO-to-H$_2$ conversion 3 times lower than the standard one. A CO(1-0) emission is found to correlate with the edge of the radiocontinuum emission in the outflow with a projected expansion velocity up to 50 km/s relative to the systemic velocity of the galaxy. About 10$^7$ M$_\odot$ of molecular gas is detected in the outflows, likely ejected by the the stellar winds from the recent starburst. The resonances inferred from the rotation curve indicate the possible presence of Inner Lindlbad. Resonances in the center (~ 1 kpc). The peak of the CO emission is slightly offset from the radio continuum (< 200 pc) and the nuclear starburst (NSB) would be located inside that radius. The energy released by the NSB is sufficient to explain such outflow/bubble morphology. The comparison of the outflow with hydrodynamical simulations indicate that the NSB is 3-7 Myr old and the bubble is still confined and not freely expanding.

## RADIO CONTINUUM

The 3.5 and 20cm data were obtained with the VLA with a spatial resolution of 1.3-2´´ (see Fig. 1). At 20cm with a total flux of 90 mJy, the observation is slightly resolved out (133 mJy for single dish). The 3.5cm total flux is 3.5cm. It indicates a slightly flattening spectra with respect to 6cm. The best power-law fit for the measurements between 325 MHz and 8.4 GHz is found with a spectral index of -0.46.

The main features of the VLA radio continuum data are the following:

- Point-like at both frequencies associated with the AGN.
- Bubble-like radio continuum, quite symmetric, reaching a projected height of 1kpc above the plane. Note that the bubble center is slightly offset with respect to the radio nucleus.
- The 20cm flux of the southern part is about twice the flux of the northern part.
- At 20cm about 10 % of the flux is thermnal, whereas it reaches 50 % at 3.5cm.
- The spectral index (see Fig. 2) in the bubble is on average steeper than -0.5, with the exception of a "hot spot" located 4" northern than the nucleus which has a flatter index (-0.4:-0.2).

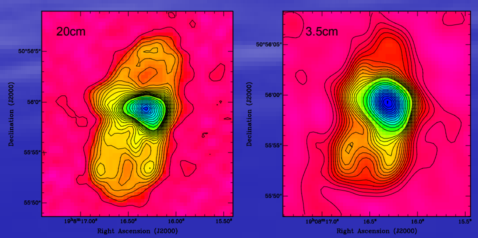



Fig. 1: Radiocontinuum at 20cm (Left) and 3.5cm (Right) from the VLA, with a spatial resolution of 1.3 and 2´´ respectively. The contours are starting from 0.1 mJy/beam with a step of 0.25 and 0.1 mJy/beam resp. for the 20 and 3.5cm observations.

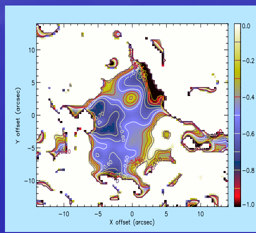



Fig. 2: Spectral index between the 20 and 3.5cm radiocontinuum

## MOLECULAR GAS DISTRIBUTION

As a tracer of the molecular gas, the transition lines CO(1-0) and CO(2-1) (114.3 and 228.6 GHz resp.) were observed with the IRAM PdB Interferometer with a velocity resolution of 10 km/s. The synthetised maps of the CO(1-0) and CO(2-1) transition lines have a respective spatial resolution of 1.6"x2" and 1.2"x1.2". On Fig. 3 the integrated intensity of both transitions are shown. Single dish observations of CO(1-0) indicate that about 50 % of the flux is filtered out by the interferometer.

The CO emission is extremely peaked towards the center of NGC 6764 and reaches a maximum at a projected distance of 1.25" (~190 pc) from the radio continuum peak. More than 98 % of the CO(1-0) flux is concentrated within the inner 800 pc.

The CO(1-0) emission shows extensions along the bar towards the western side (dubbed "W") and in a less extent to the eastern side. Assuming that the external spiral arms of NGC 6764 are trailing, this CO extension is located along the leading edge of the bar.

The comparison with the 20cm radio continuum emission shows clearly that the CO(1-0) emission correlates well with the northern bubble-like radio continuum. Since that bubble is developping perpendicular to the plane (density gradient), it shows that a molecular outflow is at play in the center of NGC 6764.

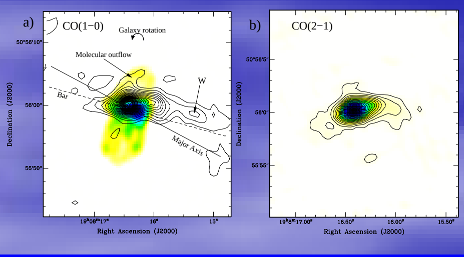



Fig. 3: Integrated intensity for the CO(1-0) and the CO(2-1) transition with the 20cm radio continuum (color) for The CO(1-0) integrated intensity map. The contours for CO(1-0) are 1,3,..,27 Jy/beam and for CO(2-1) 3,6,...,54 Jy/beam. The position of the major axis and the bar are shown respectively by the solid and dashed lines.

## CO LINE RATIO

**The line ratio between the CO(2-1) and the CO(1-0) transitions is computed by matching the spatial resolution of the two integrated intensity map (see Fig. 4). The maximum line ratio is found to be 0.98, but does not correlate with the CO(1-0) peak. This ratio is interpreted as arising from moderately warm, dense and optically thick gas.**

**On Fig. 5 the maximum line ratio in the center of NGC 6764 is computed for each channel of 10 km/s. The most striking feature is the increase of the CO line ratio for the blueshifted velocited, where it reaches values as high as 2.0. We interpret this high line ratio by the effects of the AGN/SB on the gas (X-rays, stellar winds, radio jet).**

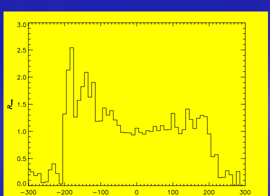
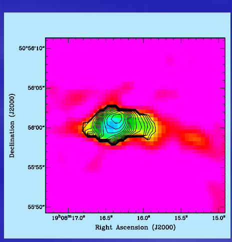


Fig. 5: CO(2-1) to CO(1-0) maximum line ratio computed in the center of NGC 6764 for each 10 km/s channel.

Fig. 4: CO(1-0) Integrated intensity overlaid by the CO(2-1) to CO(1-0) line ratio integrated over all channels. The contours are from 0.2 up to 0.95 by step of 0.05




## MOLECULAR GAS KINEMATICS

Fig. 6 shows the CO(1-0) channel map at 10 km/s velocity resolution. CO(1-0) emission is detected at 2.5σ level from 2210 to 2600 km/s (LSR). Two CO(1-0) peaks are present in the very center at negative (-120:20 km/s) and positive (-90:190 km/s) velocities, separated by 2". Extended features are showing up: the one from -40 to 130 km/s (see Fig. 9) is associated with the molecular outflow. The redshifted velocities are compatible with z-motions up to 8" (~1.2kpc) above the plane. The western feature ("W") has a large velocity extent from -80 to 10 km/s.

The dynamical center, fitted from the CO velocity field, is spatially coincident with the optical and radio continuum nuclei, indicating that the CO peak is slightly offset of the dynamical center. The largest streaming motions are located on the eastern side, correlated with the molecular outflow.

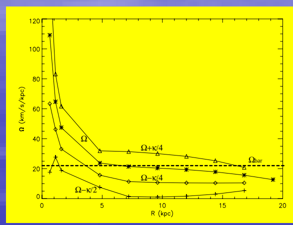



Fig. 7: Azimutal frequency Ω (asterisk) estimated from HI+CO data. The UHR (diamond) and ILRs (cross) are estimated by setting the bar corotation at the semi major axis of the bar (~40").

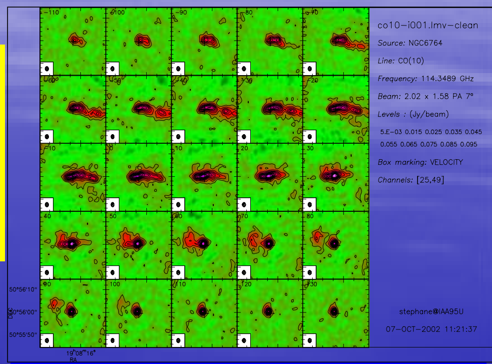


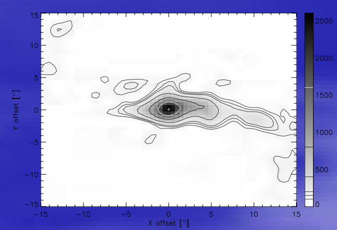

Fig. 6: Channel maps for the CO(1-0) transition line centered on the rest velocity of NGC 6764, 2400 km/s.

RESONANCES:
The resonances play a key role in the distribution and dynamics of the molecular gas.
From the CO(1-0) and HI data (Wilcots et al. 2001) the rotation curve was computed, and the azimutal (Ω) and radial (κ) frequency was derived (see Fig. 7).
Two Inner Lindblad Resonances (ILRs) are (marginallly) detected at a radius of 6 and 10": numerical simulations (e.g. Combes & Gerin 1985) show that molecular gas forms a ring located beyween the two ILRs and goes decreasing in radius with time. This ring can be partially formed with the region W. An inner ring can be present as well at the inner UHR, but the field of view of the PdBI does not allow to confirm such prediction.

## H2 MASS

Adopting a standard conversion factor CO-to-H$_2$ (Strong et al. 1988), the total mass of molecular gas is found to be 1.5 10$^9$ M$_\odot$. But this conversion factor is derived from the Galactic disk molecular gas which can be different in the center of the galaxies (density, T). From the optical extinction and the dust mass computed in the center of NGC 6764 we find that this conversion factor is probably overestimated by a factor 2-3 the molecular gas mass. The following H$_2$ mass are nevertheless given using the standard conversion factor to facilitate comparisons with other works.
In the center the molecular gas surface density (see Fig. 8) is higher than 2500 M$_\odot$.pc$^{-2}$. In the molecular outflow the surface density drops to about 100 M$_\odot$.pc$^{-2}$. About 10$^7$ M$_\odot$ of molecular gas is thus present in the outflow.

Fig. 8: Gas molecular surface density mass adopting a standard conversion factor. The galaxy inclination is taken as 61.5°




## MOLECULAR OUTFLOW

**The most striking result of our observations is the finding of a molecular outflow associated with the radio continuum bubble. The radio continuum map shows that the bubble has an in-plane projected radius of 500 pc and a projected height of 1.1 kpc. It is due probably to the intense young starburst (3-5 Myr) present in teh center of NGC 6764 (Schinnerer et al. 2000): hydrodynamic simulation of such evoluting bubble match the age computed for the nuclear starburst.**

**The energy budget of the gas phase in the bubble is computed: a total of 3.6 10$^{53}$ ergs is computed for the kinetic energy. By adopting an ad doc mass distribution model, the total potential energy is estimated to be ~10$^{55}$ ergs far much larger than the kinetic energy. For the star formation rate at play in the center of NGC 6764 (~ 1M$_\odot$/yr) the various models predict an energy release of 10$^{54}$-10$^{55}$ ergs wich is compatible with the molecular gas energy in the outflow. The energy budget of the X-rays emitting gas is two order smaller than such estimation.**

**The molecular gas (~10$^7$ M$_\odot$, see spectra on Fig. 9) ejected by the starburst off-the-plane should fall back in the galaxy disk in few Myr and possibly create a new star formation increase. Hydrodynamic models indicate nevertheless that the bubble is still pressure confined and not freely expanding.**

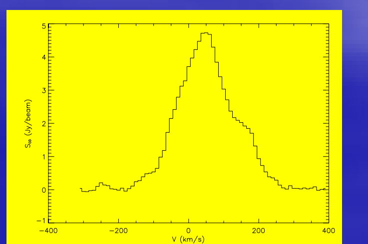



**Fig. 9: CO(1-0) spectra within a 5"x3" box located 3" northern than the CO peak, at the position of the molecular outlow.**