Letter to the Editor

First detection of molecular gas in the shells of CenA[★]

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Abstract. Shells are faint arc-like stellar structures, which have been observed around early type galaxies and are thought to be the result of an interaction. HI gas has recently been detected in shells, a surprising result in view of the theoretical predictions that most of the gas should decouple from stars and fall into the nucleus in such interactions. Here we report the first detection of molecular gas (CO) in shells, found 15 kpc away from the center of NGC 5128 (CenA), a giant elliptical galaxy that harbors an active nucleus (AGN). The ratio between CO and HI emission in the shells is the same as that found in the central regions, which is unexpected given the metallicity gradient usually observed in galaxies. We propose that the dynamics of the gas can be understood within the standard picture of shell formation if one takes into account that the interstellar medium is clumpy and hence not highly dissipative. The observed metal enrichment could be due to star formation induced by the AGN jet in the shells. Furthermore our observations provide evidence that molecular gas in mergers may be spread out far from the nuclear regions.

Key words: galaxies: individual: Centaurus A – galaxies: interactions – galaxies: ISM – galaxies: jets – radio lines: galaxies

1. Introduction

Early type galaxies (E/S0) are often found to be surrounded by faint arc-like stellar structures, called shells or ripples (Malin & Carter 1980), due to the accretion and subsequent merging of a smaller companion galaxy. It is widely accepted that the high frequency of galaxies with shells ($\sim 50\%$) attests to the importance of merging in galaxy formation (Schweizer & Seitzer 1988, 1992). Simulations of the *stellar component* have shown that the shells or ripples are created either by "phase-wrapping" of the tidal debris of the accreted companion on nearly radial orbits (Quinn 1984), or by "spatial-wrapping" of matter in thin disks (Dupraz & Combes 1987, Hernquist & Quinn 1989).

CenA is a giant elliptical galaxy with strong radio lobes on either side of a prominent dust lane situated along its minor axis (Clarke et al. 1992). Additionally, optical and HI observations (Dufour et al. 1979, van Gorkom et al. 1990) show a warped gaseous disk which has been accreted along the minor axis of this apparently prolate elliptical galaxy. CO mapping suggests that the disk contains 2×10^8 M$_\odot$ of molecular gas (Eckart et al. 1990). Recently, mid-IR observations revealed the presence of a bisymmetric bar-like distribution of hot dust in the inner disk (Mirabel et al. 1999). High contrast optical images of the galaxy show stars distributed in a large number of faint narrow shells around the galaxy (Malin et al. 1983). The presence of the warped gas disk and shells suggests that CenA has accreted one (or more) smaller disk galaxy(ies) approximately $\sim 10^8$ yrs ago (Quillen et al. 1992).

Schiminovich et al. 1994 detected 4×10^8 M$_\odot$ of HI gas associated with the stellar shells, having the same arc-like curvature but displaced 1 arcmin to the outside of the stellar shells. This result is intriguing since in general it is thought that the dynamics of the gas and stellar components are decoupled during a merging event. Detailed numerical modeling of the infall of a small companion on a massive elliptical has demonstrated that aligned and interleaved shells are formed through phase wrapping of the companion's stars on almost radial orbits (Quinn 1984, Dupraz & Combes 1987). When gas is taken into account, due to its dissipation it rapidly concentrates in the nucleus and does not form any shell (Weil & Hernquist 1993). Another possibility is that shells result from space wrapping when the relative angular momentum of the two galaxies is high. In this case the stellar shells do not have the same regular structure (Prieur 1990) and as they rotate around the central potential they dissolve more rapidly. The gas could remain associated with the stellar shells during a few dynamical times before condensing to the center. The morphology of the shells in CenA, though, suggests a combination of both phase and space wrapping since there are both a number of shells aligned with the major axis of the prolate giant elliptical and there are a few which are irreg-

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ular. Furthermore, the HI is mostly associated with what Malin et al. (1983) called the diffuse shells.

To explain the presence of gas in phase-wrapped shells, one should consider the interstellar medium as multiphase: a large fraction of the ISM could be composed of dense clumpy material with low dissipation. During a galaxy merger the dense gas behaves almost as collisionless particles and can orbit through the center as the stars do. To trace this dense component we attempted to detect molecular gas from the shells in CenA. The results were positive beyond our expectation, as described now.

2. Observations and data reduction

The observations have been carried out in May 1999 in La Silla, Chile, with the 15m Swedish-ESO Submillimeter Telescope (SEST) (Booth et al. 1989). We used the IRAM 115 and 230 GHz receivers to observe simultaneously at the frequencies of the $^{12}CO(1-0)$ and the $^{12}CO(2-1)$ lines. At 115 GHz and 230 GHz, the telescope half-power beam widths are $44''$ and $22''$, respectively. The main-beam efficiency of SEST is $\eta_{mb} = T_A^*/T_{mb}$=0.68 at 115 GHz and 0.46 at 230 GHz (SEST handbook, ESO). The typical system temperature varied between 300 and 450 K (in T_A^* unit) at both frequencies. A balanced on-off dual beam switching mode was used, with a frequency of 6 Hz and two symmetric reference positions offset by $12'$ in azimuth. The pointing was regularly checked on the SiO maser R Dor as well as using the continuum emission of the nucleus of CenA. The pointing accuracy was $4''$ rms. The backends were low-resolution acousto-optical spectrometers. The total bandwidth available was 500 MHz at 115 GHz and 1 GHz at 230 GHz, with a velocity resolution of 1.8 km s^{-1}. We mapped four regions of CenA associated with HI and stellar shells (noted as S1–4 in Fig. 1a). Regions S1 and S2 were covered with a 3×3 half CO(1-0) beam maps centered at α=13h26m16.1s, $\delta=-42°46'55.7''$ and α=13h24m35.4s, $\delta=-42°08'34.9''$ (J2000) respectively. S3 consisted of a series of pointings along an optical shell and S4 was a single pointing. The rms noise per pointing was $\sigma_{mb} \sim 3$ mK for both frequencies.

3. Results and discussion

We detected CO emission from two of the fully mapped optical shells (S1 and S2) with associated HI emission, indicating the presence of $4.3×10^7$ M$_\odot$ of H$_2$ assuming the standard CO to H$_2$ conversion ratio. The CO lines were detected at the 4σ level in four out of the nine pointings of each 3×3 map. Fig. 1 shows an optical image of CenA, with the positions mapped in CO, the location of the HI and stellar shells, as well as the spectra of the strongest CO detections found at the central position of each map. The molecular gas in both positions is clearly associated with the HI shells since their velocities (340 km s^{-1} for S1 and 720 km s^{-1} for S2) follow the velocities of the HI as presented in Fig. 3 of Schiminovich et al. 1994. The width of CO lines is ~ 20 km s^{-1} while in a beam of twice the size the HI linewidth is 80 km s^{-1}. This difference is easily explained by the systematic velocity gradients within the beams.

Table 1. HI and CO gas properties

	Center	Shell S1	Shell S2
M(HI)[a] (M$_\odot$)	$3.5×10^8$	$2.14×10^7$	$2.17×10^7$
M(H$_2$) (M$_\odot$)	$3.3×10^8$	$1.7\pm0.1 × 10^7$	$2.2\pm0.1 × 10^7$
M(HI)/M(H$_2$)	1.06	1.25	0.99
CO(2-1)/CO(1-0)	0.5[b]	0.55	0.75

[a] Based on the maps of Schiminovich et al. 1994.
[b] Using the published values of Eckart et al. 1990.

As shown in Table 1, the ratio between the H$_2$ mass (derived from the CO emission) and the HI mass found in the same area is nearly unity for both detected shells and central regions. In fact, the mass ratio between H$_2$ and HI that we find in CenA is about normal for giant spiral galaxies, where the global M(H$_2$)/M(HI) has been found on average to be equal to unity in a survey of 300 objects (Young & Scoville 1991). According to the type of the galaxy and its star formation activity as measured by the far-infrared flux, this ratio could vary (Sage 1993). It has been found equal to M(H$_2$)/M(HI)=0.2 in the Coma supercluster (Casoli et al. 1998), and it is even much lower (by a factor 10) in dwarf galaxies (Taylor et al. 1998).

The total gas mass found in CenA is almost 10^9 M$_\odot$, comparable to that of a giant spiral galaxy. Since this gas must have once belonged entirely to the accreted companion, we can deduce that the latter was not a dwarf, but a massive spiral such as the Milky Way. This also explains the large ratio of CO emission to HI gas observed, leading through the standard conversion ratio to the high values of M(H$_2$)/M(HI) found. More surprising is the fact that this ratio is the same (close to unity) in the center, and at 15 kpc from it. In general for most galaxies, due to the metallicity gradient (Vila-Costas & Edmunds 1992), the ratio decreases exponentially with radius from about 30 in the central part to less than 0.1 in the outermost parts where CO is detected (Combes 1999). Furthermore the CO(2-1)/CO(1-0) ratio in the shells, corrected for the different beam sizes, is ~0.6. This is not much lower than the 0.9 observed in the nuclei of nearby spirals (Braine & Combes 1992) and slightly above what is found in disks. This means that CO lines are not highly subthermally excited and therefore the density of the gas is at least 10^4 cm^{-3}.

Our data reveal the presence of dense molecular gas in the shells. This presence helps to understand the existence of HI shells, the HI gas being the diffuse envelopes of the dense molecular clumps, the interface between the interstellar radiation field and the clumps. Should this diffuse gas be present alone, it would have been driven quickly towards the center during the stellar shells formation. Modeling of the ISM should take into account a multiphase medium with a low dissipation gaseous component. Such models have been developed by numerically simulating the gas dynamics through a cloud-collision scheme (Kojima & Noguchi 1997, Combes & Charmandaris 1999). In these simulations the low dissipation of gas enables a fraction of it to follow the stellar component. However, due to a different initial distribution of gas and stars in the companion galaxy, the gaseous shells do not coincide with the stellar ones. More pre-
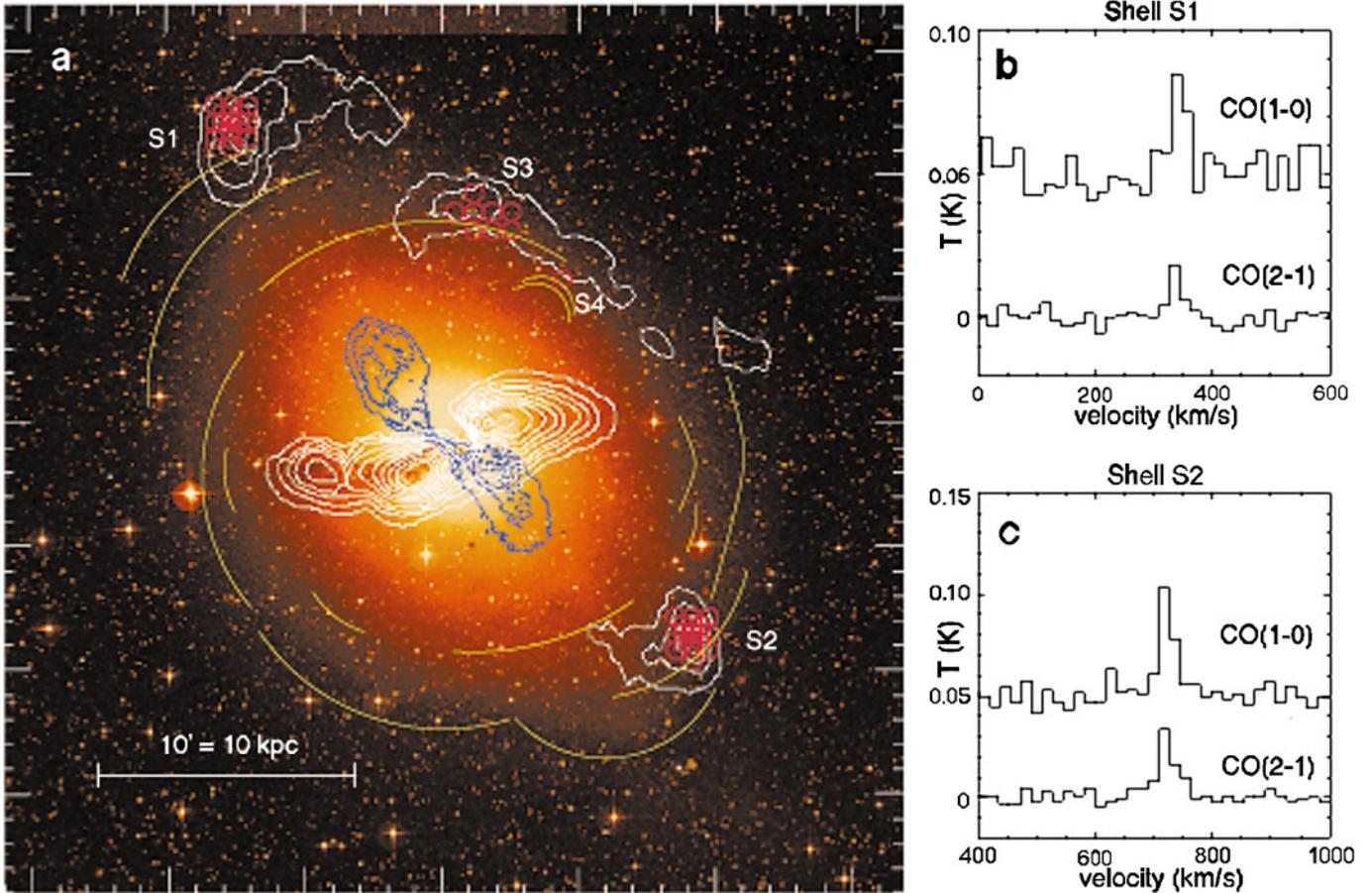
Fig. 1. a A Digitized Sky Survey optical image of CenA with the contours of HI gas (from Schiminovich et al. 1994) superimposed in white. The HI contour levels are 1, 4, 7, 10, 15, 30, 35, 40×10^{20} cm^{-2}. North is up and east is to the left, while the image scale is shown by the horizontal bar. The positions observed in CO are marked with the red circles whose size corresponds to the SEST $44''$ beam of CO(1-0). The type of each map (half-beam spacing or simple pointing) is evident by the placement of the circles. The locations of the outer stellar shells are underlined by the yellow solid lines (see also Fig. 1a of Schiminovich et al 1994). The inner 6cm radio continuum lobes (from Clarke et al. 1992) are depicted by the blue contours (contour levels 0.01, 0.05, 0.1 Jy/beam). Note the jet alignment with the location of the CO detections. The outer radio lobes are far more extended. **b** CO(1-0) and CO(2-1) spectra towards the northern shell S1 with the temperature scale in main beam T_{mb}, smoothed to 18 km s^{-1}. **c** Same as in b) but for the southern shell S2.

cisely the gas is radially more extended in the companion disk than the stars and therefore less gravitationally bound. Hence, during the merger the gas is the first to be tidally stripped from the companion and thus does not experience dynamical friction. On the other hand, dynamical friction brakes efficiently the remaining stellar core which is tidally stripped somewhat later in the merging process. Since the stars have lost more energy than the gas they oscillate in the potential with smaller apocenters and thus the shells they form are located inside the gas shells. In this framework the observed displacement of the gas with respect to stars in CenA shells is naturally explained. The presence of a diffuse gas (seen in HI) at those regions is expected since part of the clumpy gaseous component dragged into shells will be dissociated either by local star formation activity or by the global galactic radiation field.

What remains unclear is *why the metallicity in the shells is sufficient for the CO emission to be detected*. Indeed as described above, the dynamical friction segregates the gas in the elliptical potential according to its initial distribution in the companion and a metallicity gradient should still exist in the final merger remnant.

A solution to this puzzle could be found if we consider the effect of the radio jet of CenA on the gaseous shell. Note that from the four shells mapped in CO emission only the two shells (S1, S2 in Fig. 1) *aligned with the jet* have been detected. Optical filaments are observed along the jet, only in the regions where the jet and the shells intersect, suggesting that the ambient gas is ionized by the nuclear beamed radiation or is excited by shocks (Graham & Price 1981, Morganti et al 1991). Moreover, a group of blue stars has been discovered, just between the northern HI shell and its corresponding outermost optical filament (see Fig. 1 and 2 in Graham 1998 and Graham 1999). The formation of these stars is proposed to be triggered by the impact of the radio jet on the HI shell. The HII regions ionized by these blue stars have measured velocities coinciding with those of the adjacent HI and CO gas. A study of the stellar con-

tent reveals several generations of stars whose lifetimes extend over a period of 15×10^6 years, while supernovae dissipate into the surrounding medium in less than 10^6 years (Graham 1999). This observed stellar activity has certainly enriched the observed gas in metals and can explain our detection of CO molecules. Moreover, the impact of the radio jet could be responsible for the formation of new dense molecular clouds. It is necessary, however, that some of the gas was already present in the jet region, and this gas be driven there by the shells. The formation of gaseous shells requires the presence of dense molecular gas first, since the jet can only maintain or form secondary molecular clouds (as quoted by Graham 1998), but cannot serve as their primary formation mechanism. Indeed, we can eliminate the alternative possibility in which diffuse gas is spread by the interaction everywhere, and is compressed in molecular clouds in the jet; there would then be no coincidence between the HI gas and the stellar shells in this scenario.

4. Conclusions

We have detected CO molecules in two shells aligned along the major axis of Centaurus A. The molecular gas is globally associated with the HI and stellar shells but with a radial shift, the HI being the more external component, and the stars the more internal. The presence of molecular clouds in these distant shells is compatible with the dynamical scenario of phase-wrapping, following the merger of a spiral galaxy with Centaurus A. Part of the interstellar medium of the spiral is clumpy, with very low collision rate and dissipation, and can follow nearly radial orbits during the merger, like the stellar component, without accumulating towards the center. The differential dynamical friction experienced by the gas and stellar components, that are unbound from the spiral companion at different epochs, can explain the radial shifts between the different shells.

The detection of CO emission far from the center implies the presence of H_2 molecules as far as $1.16\,R_{25}$. The present detections, taking into account that only a small fraction of the shells was mapped in CO, suggest that more than 50% of the gas in the outer regions of CenA is in molecular form, and at least 10% of the total molecular gas detected in CenA is not in the nucleus. Moreover the derived HI/H_2 mass ratio is nearly constant with radius. This requires a metallicity enrichment in the most external gas, that could be due to the interaction between the gaseous shells and the radio jet. This prototypical example of a gaseous accretion suggests that the molecular gas is not always confined in the nuclear regions in merger remnants.

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