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A molecular gas bridge between the Taffy galaxies

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Abstract. The Taffy Galaxies system, UGC 12914/5, contains huge amounts of molecular gas in the bridge region between the receding spirals after a direct collision. 2–9 × 10^9 $M_\odot$ of molecular gas is present *between* the galaxies, more than the CO emission from the entire Milky Way! Such dense gas can only be torn off by collisions between dense clouds, in this case with relative velocities of about 800 km s^{-1}, such that the remnant cloud acquires an intermediate velocity and is left in the bridge after separation of the colliding galaxies. We suggest that after ionization in the collision front, the gas cooled and recombined very quickly such that the density remained high and the gas left the colliding disks in molecular form.

Key words. galaxies: spiral – galaxies: evolution – galaxies: ISM – galaxies: interaction – galaxies: individual: UGC 12914 – galaxies: individual: UGC 12915

1. Introduction

Galaxy interactions are major drivers of galaxy evolution. Outside of clusters, most interactions are tidal, in which the relative velocities are similar to or less than the galactic rotation velocities, and can result in morphological changes and/or galaxy merging. The other type of interaction is a direct collision at speeds well beyond galactic rotation velocities such that tidal forces do less damage than the collision itself (Struck 1999). These "direct collisions" are rarer. In a spiral-spiral direct hit, the stars essentially pass right through the disk of the other galaxy because of the low likelihood of stellar collisions. The pressure exerted by gas clouds (column density $\lesssim 10^{23}$ protons cm^{-2}) has no effect on the stars (column density $\gtrsim 10^{34}$ protons cm^{-2}). The "damage" is mostly caused by collisions of gas clouds in the spiral disks. The direct hits involving gas-rich galaxies are really ISM-ISM collisions, in which gas is dragged from the spiral disks into the space between the two systems. However, because the gas mass is a small fraction of the disk mass in spirals, these collisions tend not to form mergers as the stars pass right through. Tidal interactions can eject gas (and stars) as well but in tidal tails rather than a gaseous bridge.

The interacting pair of galaxies, UGC 12914/5, is one of the best examples of a strong ISM-ISM collision. Condon et al. (1993), hereafter C93, observed the system with the VLA in the HI line and 6 and 20 cm continuum emission. They found that the bridge between UGC 12914 and UGC 12915 emits strong synchrotron emission, with the magnetic fields being stretched as the galaxies separate, hence their naming the system the Taffy Galaxies. C93 showed that the collision was indeed close to head-on, with the nucleus of UGC 12915 passing through the more massive UGC 12914 slightly North of its center. The disks are counter-rotating and the recession velocities are nearly the same, so that the relative velocities are essentially transverse. Both disks are massive judging from the size of the system and the rotation velocities (260 and 310 km s^{-1} for UGC 12915 and 12914 respectively). C93 estimate that the collision occurred about 20 Myr ago with a transverse velocity of about 600 km s^{-1}. Considering the counter-rotation and the transverse velocity, the speed at which clouds collide is some 800 km s^{-1}.

In this work we present ^{12}CO and ^{13}CO spectra and an optical slit spectrum of the Taffy system. Recent studies have shown that, as predicted by C93, the synchrotron bridge contains little dust (Jarrett et al. 1999; Zink et al. 2000), presumably because the shocks have destroyed most of the grains. The extremely interesting feature is that *huge quantities of molecular gas are present in the bridge region*. Smith & Struck (2001) presented a CO spectrum showing CO in the bridge region. For consistency with previous work, we assume a distance to the Taffy galaxies of 60 Mpc, corresponding to $H_0 = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. Observations

The millimeter-wave observations were carried out with the 30 m antenna on Pico Veleta, Spain, operated by the Institut de RadioAstronomie Millimétrique (IRAM). The data presented

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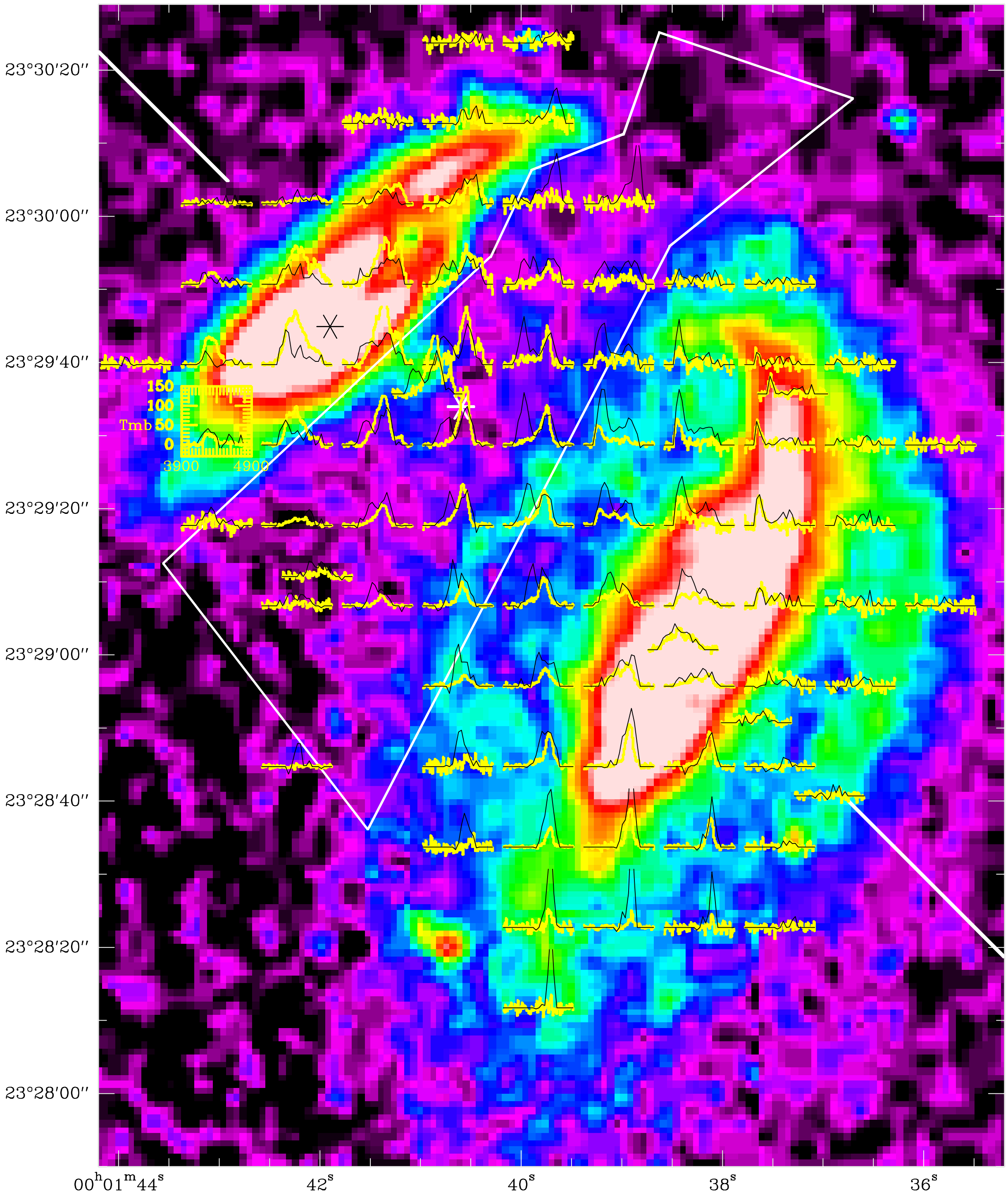

Fig. 1. CO(1–0) spectra (yellow line and yellow scale, intensity in milliKelvins) overlaid with HI spectra (black line) on a Digitized Sky survey image of the UGC 12914/5 system. The center of UGC 12915 is at 00^{h}01^{m}41.9^s, 23°29′44.9″ and the HII region is at 0^{h}1^{m}40.6^s, 23°29′33.9″ and these are the positions shown in Fig. 2 and marked with stars here. The HI emission extends far south in UGC 12914 (lower right). Lines mark the ends of the slit which roughly connects the nuclei. The bridge region is delimited by the white polygon.

here are from several runs from 1998 to 2001. All data are presented using the main beam temperature scale, appropriate for small sources (see observing details in Zhu et al. 1999; Braine et al. 2001). The spatial resolutions (beam size at full width half maximum) are 22″ and 11″ for respectively the $J = 1 \rightarrow 0$ and $J = 2 \rightarrow 1$ transitions of ^{12}CO and ^{13}CO.

In Fig. 1, we present an optical image of the UGC 12914/5 system with our CO(1–0) spectra (yellow line) and HI spectra (black line) from C93 superposed.

In Fig. 2, we present our ^{12}CO and ^{13}CO spectra for the giant HII region in the bridge and for UGC 12915. The $^{12/13}$C abundance ratio is expected to be about 60, so the rarer

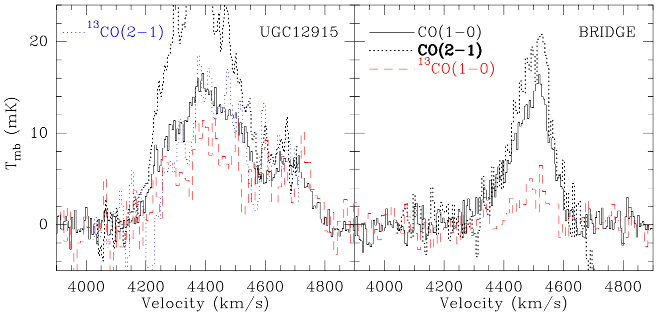

Fig. 2. ^{12}CO and ^{13}CO spectra for UGC 12915 (left) and the giant HII region (right) in the bridge. The ^{12}CO line intensities are divided by 10. The angular resolutions are respectively 11″ and 22″ for the (2–1) and (1–0) transitions.

^{13}CO species can be used to estimate optical depth. The ratio of the ^{12}CO to ^{13}CO line intensities is very different in the two regions shown. In the center of UGC 12915 the ratio is about 15 (19 in the $J = 2 \rightarrow 1$ transition, a value between the standard 7–10 (Sage & Isbell 1991) and the high values observed in the very IR-bright galaxies (Casoli et al. 1992). The optical depth of the CO lines in the bridge is clearly much lower, as the ^{12}CO to ^{13}CO line ratio is about 50 in the (1–0) transition and ^{13}CO(2–1) is undetected, such that the intensity ratio is $\gtrsim$100.

The optical long-slit spectra were taken with the Carelec spectrograph (Lemaître et al. 1990) on the 1.93 m telescope of Observatoire de Haute-Provence in November of 2002. The CCD was an EEV 2048 × 1024, with a pixel size of 13.5 μ, which corresponds to spectral and spatial resolutions of 1.78 Å and 0.58″ respectively. We obtained a 45 min spectrum of the pair of galaxies with the slit aligned with the nucleus of UGC 12914 and the giant HII region as shown in Fig. 1. Spectra of standard stars were obtained on a different night.

The main goal of these observations was to determine how the ionized gas is excited: by young stars from a recent starburst or by shocks. The line ratios indicate that the gas in the nucleus of UGC 12915 and in the giant HII region are photoionized, and that UGC 12914 is a LINER. The metallicities from OIII/Hβ line ratios are subsolar – $12 + \log(\mathrm{O/H}) = 8.5 \pm 0.2$ and 8.7 ± 0.3 for the giant HII region and the nucleus of UGC 12914 respectively. Figure 3 shows the optical spectra of UGC 12914, UGC 12915, and the giant HII region.

3. Gas masses and the bridge region

Integrating over the entire region observed in CO(1–0) and using a "standard" conversion ratio $N(\mathrm{H}_2)/I_{\mathrm{CO}} = 2 \times 10^{20}$ cm^{-2} per K km s^{-1} to convert the CO emission into an H$_2$ column density, our estimate of the total gas mass (H + He) in the molecular clouds is 3.5×10^{10} $M_{\odot}$. 25% of the CO emission comes from the bridge region, representing more gas than in the whole of the Milky Way! *How can so much molecular gas be pulled out of a galactic disk and what does this fact tell us about the ISM?*

First, let us address the question of the $N(\mathrm{H}_2)/I_{\mathrm{CO}}$ conversion factor. The "standard" factor used in the calculation above, $N(\mathrm{H}_2)/I_{\mathrm{CO}} = 2 \times 10^{20}$ cm^{-2} per K km s^{-1}, is likely overestimated for galactic nuclei and starburst galaxies. While neither UGC 12914 nor UGC 12915 are strong starbursts, UGC 12915 is a strong FIR emitter *and* its CO emission is rather centrally concentrated. In UGC 12914, the situation is the reverse – most of the CO emission comes from the disk, with CO detected out to distances of 10–12 kpc from the center. We tentatively conclude that (a) the true H$_2$ mass of UGC 12915 could be overestimated by up to a factor ~4 but (b) the H$_2$ mass of UGC 12914 is unlikely to be grossly overestimated.

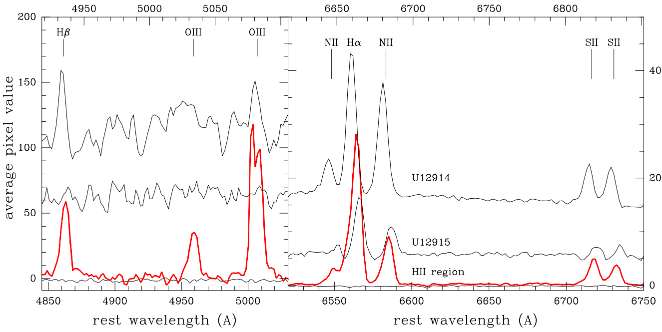

Fig. 3. Optical spectra of the Taffy system around the Hβ and Hα lines. Top line is nucleus of UGC 12914 (intensities divided by 2), followed by UGC 12915 and the giant HII region (thick red line). No emission is detected (bottom line) between the HII region and the outer ring of UGC 12914. The OI 6300 Å line is also detected in UGC 12914 and the HII region and is about 0.3–0.5 as strong as the NII 6548 Å line.

Table 1. Average CO(1–0) intensities for each region in K km s^{-1}, CO(1–0) luminosity in K km s^{-1} pc^2, and HI and H$_2$ masses in solar units. The two values given for the HI mass in the bridge are the HI mass in the same region as the CO (see Sect. 3) and the total bridge HI mass. The H$_2$ mass range takes into account the possible errors in the $N(\mathrm{H}_2)/I_{\mathrm{CO}}$ conversion as discussed in Sect. 3. The hydrogen masses include helium in order to give the total gas mass.

	bridge	U12914	U12915
$\langle I_{\mathrm{CO}} \rangle$	12.2	6.2	16.4
$L_{\mathrm{CO}(1\rightarrow0)}$	2.0×10^9	2.7×10^9	3.2×10^9
M_{HI}	$2, 5 \times 10^9$	7.5×10^9	2.7×10^9
M_{H_2}	2–9 $\times 10^9$	5–10 $\times 10^9$	3–6 $\times 10^9$

How much molecular gas is present in the bridge region? The large amount of molecular gas was not predicted by C93, who expected that (*a*) the molecular gas was too dense to be pulled out and (*b*) the molecules involved in collisions strong enough to blow a molecular cloud out of a disk would be shock destroyed. Our observations show that this is not the case.

As noted in Sect. 2, the optical depth of the CO lines is clearly lower in the bridge because of the high $^{12/13}$CO intensity ratio (Fig. 2). As predicted by C93, and attributed to dust destruction, the FIR emission in the bridge region is weak (Zink et al. 2000). Dust mantles contain a lot of carbon and oxygen which, when expelled from the grain, can increase the gas-phase CO abundance. Because the CO emission here is not very optically thick, increasing the CO abundance can increase the intensity of the CO emission per H$_2$ mass. The low optical depth and increase in CO abundance due to grain destruction taken together could decrease the $N(\mathrm{H}_2)/I_{\mathrm{CO}}$ ratio by a factor of a few as compared to the "standard" value. A more precise estimate of the molecular gas mass is currently impossible. Nonetheless, even reducing the bridge molecular gas by a factor of four means that the bridge alone contains as much or more H_2 as the whole Milky Way!

The geometry of the collision in the Taffy system maximizes the cloud collisions and is probably unusually efficient at drawing gas out of the disks. What kind of collision is capable of bringing some 10^{10} $M_\odot$ of gas out of the disks? Many of the line profiles (Fig. 1) in the bridge region show double HI peaks. The CO is systematically coincident with the higher velocity HI peak. The low-velocity HI peak in the bridge with no CO counterpart is presumably the unperturbed HI belonging to the outer northeastern part of UGC 12914 and located behind the bridge.

One would expect head-on GMC (Giant Molecular Cloud)-GMC collisions at 800 km s^{-1} to result in ionization because the kinetic energy dissipated is close to 1 keV/proton. The magnetic field energy is negligible compared to the cloud kinetic energy dissipated in collisions so magnetic fields should not be able to pull the dense gas out of the disks.

Could much of the molecular gas have recombined in the bridge region since the collision? Braine et al. (2001) estimate the H_2 formation time to be $t_{20\%} \sim 10^7/n$ years where n is the atomic hydrogen density in atoms cm^{-3} and $t_{20\%}$ is the time for 20% of the HI to become H_2. We can estimate the density by simply taking the hydrogen column density and dividing by the size of the bridge, likely to be similar in depth and in width. Thus, for $N_{\rm H} \approx 10^{22}$ cm^{-2} and $d \approx 10$ kpc, we obtain $n_{\rm H} \approx 0.3$ cm^{-3}. Thus, in the time since collision, we do not expect more than 20% of the HI in the bridge to have recombined into H_2 – this is a small fraction of the bridge H_2 mass.

However, Harwit et al. (1987) argue that while GMC-GMC collisions result in complete ionization, the cooling time for dense (several 10^3 cm^{-3}) gas from 10^6 to below 10^4 K is less than 100 years. In such a short time the cloud volume cannot increase appreciably so the gas remains dense. The recombination time scale is quite short for such dense gas, provided the photons can escape or be absorbed by dust. If so, then the H_2 formation time as described above should also be very short due to the high density. *While most H_2 was not formed in the bridge, colliding GMCs may have been rapidly ionized only to cool and reform H_2 while the galactic disks are still passing through each other*. This would result in a H recombination line flash for each cloud collision. Such a mechanism could explain the mass of gas spread over the bridge region. Collisions between diffuse gas clouds will also result in their ionization but at the lower densities the gas will not have time to cool and recombine before cloud dissipation, hindering the formation of the large amounts of H_2 observed here.

The other clear case of a recent ISM-ISM collision is the UGC 813/6 system which also has a synchrotron and HI bridge (Condon et al. 2002). In Stephan's Quintet, in which NGC 7318b is hitting the compact group at about 800 km s^{-1}, Lisenfeld et al. (2002) have shown that about 3×10^9 $M_\odot$ of H_2 is present in the colliding region SQ A, some 20 kpc from the centers of NGC 7318a and b. It seems clear that although the velocities should result in ionization of the neutral gas, ISM-ISM collisions below 1000 km s^{-1} are extremely efficient at bringing gas out of the galaxies, even from the inner parts.

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