OBSERVATIONS OF GAS IN INTERACTING GALAXIES

F. COMBES
DEMIRM, Observatoire de Paris
61 Ave. de l'Observatoire
F-75014 Paris, FRANCE

This is a brief review of the recent progress made on this domain, earlier work is nicely summarised either in the review of Barnes & Hernquist (1992a), or in Proceedings of Rencontres de Moriond in spring 1992 (e.g. Thuan et al 1993), or of Lexington Conference in spring 1993 (e.g. Shlosman 1994).

1. Large HI extensions in interacting galaxies

The HI gas is present in the outer parts of galaxies, well beyond the optical disk. There the matter is less bound to the galaxy, and is very sensitive to tidal forces, which grow as r^2. Spectacular tidal tails and bridges are observed in HI. Several systems have recently been observed with high sensitivity and resolution with the VLA (see in particular Van Gorkom, this IAU meeting): M81/82 (Yun et al 1993), Arp 295, NGC 520 and the Mice (Hibbard et al 1993), NGC 7252 (Hibbard et al 1994).

It appears that the percentage of the total HI mass that is contained in the tidal tails is increasing during evolution towards the final merger stage. Only 20% of the HI is in the tidal tails in the M81 system, it amounts to 30% in Arp295, 60 to 65% in the Mice and NGC 520, and 75 % for NGC 7252 and NGC 3921, both advanced mergers. The total HI content, however, remains normal, between 10^9 and 10^{10} $M_\odot$.

At the same time, the molecular gas, as traced by CO emission, appears enhanced with respect to the normal contents of the spiral galaxies members, and highly concentrated towards the center. There, it can represents up to 45% of the dynamical mass (Scoville et al 1994).

We can therefore summarise the main features learnt from the gas distributions: most of the atomic gas from the outer parts of spiral disks are dragged out in the tidal tails, together with stellar material. Most of this

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gas will not escape, however. Already a large fraction of it is observed flowing back to the galaxy in NGC7252, through inward HI velocities at the bottom of the tails (Hibbard et al 1994, see also Schweizer, this IAU meeting). It is likely that some molecular gas is also pulled out in the tails, but the low metallicity of the outer parts of spiral galaxies do not allow the detection of CO emission from this gas. An even larger amount of gas is driven in, through gravitational torques and dissipation, an piles up in the nuclei of galaxies. This accounts for the large column densities observed towards the nuclei of the merging galaxies, with millimetric interferometers. Masses up to 10^{11} $M_\odot$, i.e. 10 to 50 times the normal molecular content of a spiral galaxy, are detected in the ultra-luminous infrared galaxies (Sanders et al 1991). These high concentrations of molecular matter in the nuclei explain easily the violent nuclear starbursts: the gas density is well above the critical one for global gravitational instabilities.

The fact that interactions drag a large quantity of HI far from the optical disk, has raised the idea that some of the Lyα absorptions in quasars spectra could be due to such tidal gas (Morris & van den Bergh 1994). However, this gas is not long-lived.

It is very rare to find CO extensions in maps of merging galaxies, since more than 50% of the molecular component is concentrated to the central spot (about 1.7" in Arp 220, i.e. 300pc). There are however some exceptions, like Arp 299 (Sargent & Scoville 1991), the Antennae (Stanford et al 1990), and VV114 (Yun et al 1994). These are less advanced mergers, where some star formation is enhanced in the disks, accompanying the nuclear starburst.

Such high gas concentrations in nuclei, and the violent starburst that results, solve a long-debated problem about the elliptical formation through mergers: it was objected that the central phase-space density in the cores of ellipticals is much larger than in the spiral precursors, and that in a non-dissipative merging, the phase-space density could only decrease. In fact, we know now that the gas density becomes a large fraction of the total density in merger nuclei, and the process is far from non-dissipative.

Another implication of these huge molecular contents, that far exceed the gas content of the precursors, is that invisible gas reservoirs must exist around normal galaxies, that become visible in the interactions. This will be confirmed now, through larger samples of less extreme interacting galaxies.

2. More gas in interacting galaxies

From the survey of 100 nearby spirals completed at IRAM, and the > 300 objects in the literature, Braine & Combes (1992, 1993) have studied statistically the CO emission of galaxies, in function of their environment, and interaction/perturbed state. They found that interacting galaxies have

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4 times more CO emission than non-interacting galaxies.

To investigate whether this could be due to a different H2/CO conversion ratio in interacting galaxies, we have studied the excitation conditions of the molecular gas, temperature and density, through the CO(2-1) line emission, and through density tracers, such as CS or HCN molecules with a large dipole moment. In interacting galaxies, the CO(2-1)/CO(1-0) ratio is very similar to that in non-interacting galaxies, suggesting that the gas is not warmer. Also, the HCN and CS emission is even larger relative to CO in interacting and merging galaxies, as shown by Solomon et al (1992). Therefore, there is no reason to consider a different H2/CO conversion ratio in interacting galaxies.

A study of CO emission in binary galaxies, selected by their isolation on the sky, with criteria similar to Karachensev (1972), confirms the result that there is more CO emission in interacting galaxies, and a trend with the present separation of the companion is found (Combes et al 1994).

Could this mean that there is more molecular gas in interacting galaxies, by conversion of atomic gas into molecules? It does not seem to be the case, since the HI content of galaxies does not depend on the tidal class (Braine & Combes 1993). Zasov & Sulentic (1994) confirm that there is little or no HI depletion in star-forming pairs of galaxies. Only for the most ultra-luminous infrared galaxies, that correspond to highly interacing or merging starbursts objects, the HI gas begins to be depleted (Mirabel & Sanders 1989).

Therefore, it can be concluded that interacting galaxies have more visible gas than normal galaxies. It is possible that this gas is supplied from the outer parts by the strong gravitational torques generated in the interaction, by the companion itself, and by the induced non-axisymmetric perturbations, such as spiral arms and bars. Simulations show that these torques are quite efficient to drive large amounts of gas towards the inner parts of galaxies (Barnes & Hernquist 1992b, Combes et al 1990). The gas would be cold and invisible when in quiescent state in the outer parts; it will generate a burst of star formation when arriving towards the center, because of its large density and velocity dispersion. This scenario explains the large enhancement of star-forming activity in interacting galaxies (e.g. Bushouse 1986, Sanders et al 1986).

3. Tidal dwarf formation

It has long been suggested that instabilities in the long tidal tails could form condensations of gas of masses and sizes characteristic of dwarf galaxies. Star formation has been observed in such condensations in the antennae and super-antennae (e.g. Mirabel et al 1992). Hernquist & Barnes (1994), and Elmegreen et al (1993) have shown that such condensations easily occur in N-body simulations. More generally, the ISM of interacting galaxies is likely to condense in large gaseous complexes, of say 10^8 $M_\odot$.

One of the most striking feature in interacting galaxies, is the enhanced velocity dispersions in the gaseous component. This comes from the gravitational perturbations, that produce streaming motions, asymmetries, spiral arms, strong bars, etc.. In particular, in the molecular gas of M51, the 500pc-scale average of the dispersion is 25km/s, while it is more around 6km/s in a quiet population (Garcia-Burillo et al 1993). This has the consequence to increase the critical Jeans scale for gravitational instabilities, and to create giant complexes (e.g. Rand 1993). The critical length is indeed in $\lambda \propto \sigma^2/\mu$, where σ is the velocity dispersion and μ is the gas surface density. This can explain also the formation of giant and dense star clusters (globular clusters are formed in mergers, Schweizer 1993).

4. Ram pressure versus tides in clusters

Interactions of galaxies are much more frequent in clusters. However, it is believed that the relative velocities between galaxies are then too large to produce significant perturbations. This might not be true (see e.g. Valluri, 1993).

A major problem is that it is quite difficult to disentangle between the action of the cluster as a whole, and in particular the ram-pressure of the hot cluster gas, and the tidal action of nearby galaxies. Both actions are enhanced in the cluster center (Boselli et al 1994). Recently, a spectacular manifestation of tidal interaction, mimicking ram-pressure, has been reported, in the small group of NGC 2300 (Gruendl et al 1993). The old stellar population is following the gas perturbation, rejecting the ram-pressure hypothesis.

5. Ring galaxies

Ring galaxies, although rare (less than 0.2% of all spirals), are an ideal laboratory to tackle tidally induced star-formation (e.g. Marcum et al 1992). Horellou et al (1994) have observed the molecular content of a series of ring galaxies, and found that it was also enhanced with respect to normal galaxies. In two peculiar objects, very high radial velocities have been observed in the gas (Hα in Kar29, Marziani et al 1994, in NGC 1144 or Arp118, Gao et al 1994). This means that part of the gas of the target disk in the head-on collision has been stripped away, and escapes from its parent galaxy. This has also been found independently in N-body simulations with gas (Horellou & Combes 1994).

6. Gas in shells around ellipticals

Schiminovich et al (1994) have observed HI gas associated with shells in the CentaurusA galaxy. This observation is a priori surprising, if we believe that shells are phase-wrapped stellar structures, formed during the merging of a small companion into a massive elliptical. Indeed, the gaseous and stellar component will not have the same behaviour when approaching the center of the potential well, if the matter is in quasi-radial orbits (cf Weil & Hernquist 1994). In NGC 5128, the HI is associated with the outermost diffuse shells, it is displaced to the outside of the optical shells, and has a high rotation velocity. The conclusion is that only a companion in a more circular orbit is able to produce this HI ring. However, there is no explanation for the displacement between optical and HI shells.

7. Gas in polar rings

In accretion events, while the accreted stars are dispersed in a diffuse halo, the gas can condense in a ring, either equatorial or polar, through dissipation, and cancelling out of opposite angular momenta through differential precession and cloud-cloud collisions. Dense and metallic gas has been observed through the CO line, justifying the star-formation occuring in polar rings, and the relatively long life-time of these rings (Combes et al, 1992; Watson et al, 1994; Arnaboldi et al, 1994).

8. Conclusions

Interactions between galaxies provide the external gravitational forces needed to reveal the large amounts of quiescent gas in the outer parts of galaxies. Part of the atomic gas is dragged out in huge tidal tails, that can give birth to dwarf galaxies through instabilities. Most of the gas is driven in towards the central parts, giving rise to huge nuclear starbursts, and may be nuclear activity. Meanwhile, the interactions has agitated the gas, increased the velocity dispersion, and enhanced the formation of large gas complexes. Galaxy evolution is then highly accelerated.

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