MOLECULAR SPIRAL ARMS

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ABSTRACT. The recent single-dish and interferometric mapping of the disks of nearby spirals in the CO lines are reviewed. In all galaxies with a grand-design structure molecular spiral arms are prominent, with an arm/interarm contrast of 4 or more. CO-poor spirals seem to have more contrasted CO arms. In most galaxies (NGC6946, M31, M83, M81) the CO, HI and Hα ridges are closely associated while in some regions of M51, the CO is upstream and associated with the dust lane and spiral shock. This suggests that there is no unique sequence leading from the gas to the stars in the arms. The differences between these galaxies are probably linked to the strength of the density wave, the location of the resonances and the overall gas content of the galaxy.

1. Introduction and description of the observed galaxies

Observations, as well as the theory and simulations, have shown that spiral galaxies may be either *flocculent*, with multiple and fragmented arms, or *grand-design*, with two or more well-defined arms. In the classification of Elmegreen & Elmegreen (1984) flocculent galaxies are in Arm Classes 1 to 4 while grand-design are in AC 5 to 12. Grand design spirals are generally associated with a density wave, in which case the arms are seen also in the old stellar component in the red or NIR.

In any spiral galaxy it is the star forming regions that define the spiral arms. As stars are formed inside molecular clouds, it is worth adressing the question of the existence of molecular spiral arms, in order to precise the relationship between the DW, the formation of Giant Molecular Clouds, and the star formation. Inside the arms, the presence of a density wave can organize the interstellar matter by gathering the clouds together in the arms (orbit crowding). If star formation proceeds at a normal rate inside the arms, since the gas density is higher at the end there are more stars. But the DW can also trigger the formation of Giant Molecular Complexes, for example inside atomic complexes. Finally the DW may trigger star formation inside the molecular clouds, for example by enhancing cloud-cloud collisions. These three mechanisms are likely to be at play simultaneously in real galaxies but at different rates, and this is what one would like to determine.

What can be derived from the observations ? The first quantity to determine is the arm-interarm contrast in the stellar and gas components. The HI arm-interarm contrast is not very high, with typical values of a few. In any case it is expected that the contrast will be larger in the gas than in the old stars, and in CO than in HI, just because of the velocity dispersion : $\sigma(*) > \sigma(HI) > \sigma(CO)$, so that unless the CO contrast is extremely high, this

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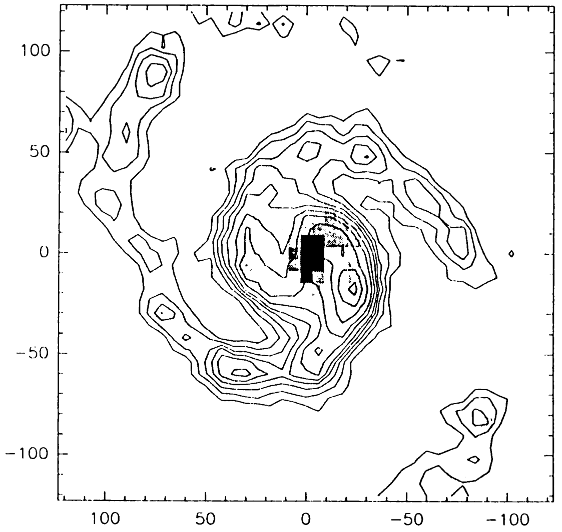

Figure 1 : IRAM CO(2-1) map of M51. Contours : CO(2-1) line area. Grey-scale : thermal radio continuum from Tilanus et al. (1989). From Garcia -Burillo (1990)

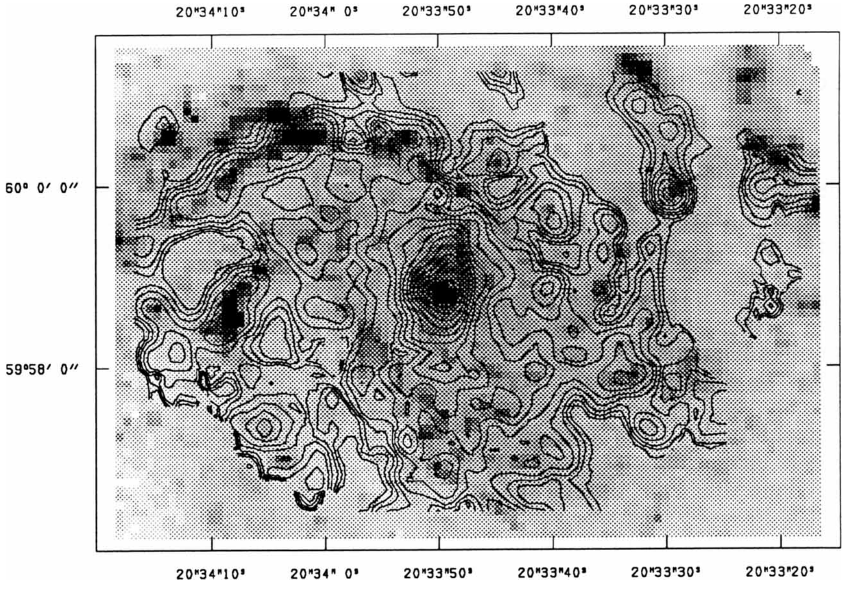

Figure 2 : Molecular spiral structure of NGC 6946. Contours: CO(2-1) line area, from the IRAM-30m telescope. Beamsize 13", sampling 10" (Clausset et al. 1990, this Symposium). Grey-scale: Hα emission

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quantity will not be very useful. Clearly, in order to quantify the importance of the three above mechanisms, mapping is necessary in order to obtain spatial and velocity information.

The problem is then that in nearby galaxies the typical resolution needed to resolve the spiral arms is about 20" (at 5-10 Mpc). For an angular extent of easily detectable CO emission of several arcmin (in NGC 6946 at this resolution 1 K lines are seen at a radius of 3'), the minimum number of points for single-dish mapping is about one thousand... As for interferometric observations, many fields are necessary to cover the whole galaxy which also leads to time-consuming projects (not speaking of the problem of short spacings). All these problems explain why usable CO maps of nearby spirals are just becoming available now.

Table 1 lists the galaxies for which we have now some information about the molecular spiral arms, in order of increasing infrared luminosity (note that H_2 masses have been computed with $N(H_2) = 2.6\ 10^{20}$ I(CO) (Kkm/s)). The first thing to note is that all these galaxies seem to have roughly the same star formation efficiency as measured by the ratios L_{IR}/L_B or $L_{IR}/M(H_2)$, although they have different kinds of spiral arms. For the two spirals with the best grand-design pattern, M81 and M51, the $L_{IR}/M(H_2)$ ratio seems to indicate that contrary to most expectations, M51 is less efficient in star formation than M81!

Table 1 : the sample of galaxies where the molecular spiral structure has been studied. * indicate that a distance ambiguity by a factor of 2 at least

	AC	Lir	ir/B	ir/H_2	$M(H_2)$	D(Mpc)	Beam	Reference
M33	5	1.1(9)	0.56	?	?	0.8	55", 12"	Wilson & Scoville 1990
M81	12	2.7(9)	0.36	7.6	3.5(8)	3.3	12"	Brouillet et al. 1990
M31	?	2.8(9)	0.1 ?	?	?	0.7	33", 12"	Kutner 1990
M101	9	8.4(9)	0.27	2.5	3.3(9)	5.5	55", 12"	Kenney et al. 1990
M83	9	1.0(10)*	0.65	2.1	5(9)	3.7	22"	Wiklind et al. 1990
N6946	9	1.0(10)*	0.67	4.3	2.3(9)	5	12"	Clausset et al. 1990
IC342	9	1.4(10)	0.61	2.7	5.2(9)	4.6	33"	Rydbeck 1990
M51	12	3(10)	0.60	2	1.3(10)	9.6	12", 2", 8"	many refs...

2. The existence of molecular spiral arms and the contrast

The first result of the observations is that as soon as the resolution is sufficient the arms are clearly seen in CO, except for very inclined galaxies (M31, M81) and M33 which is rather flocculent. Figure 1 is a a CO(2-1) map of M51 obtained with the IRAM 30m telescope, from Garcia-Burillo et al. (1990) while figure 2 is a CO(2-1) map of NGC 6946 obtained by Clausset et al. (1990) also with the 30m (13" resolution). There is a good large-scale agreement between the location of the various spiral arm tracers : red light, HII regions and molecular clouds, which allows us to speak of molecular spiral arms. This is shown for NGC 6946 in Figure 2 where the grey-scale represents the Hα emission. However there may be some small-scale discrepancies that will be discussed in Section 3.

The spiral structure also shows up very clearly in interferometric maps of M51. Rand and Kulkarni (1990) have presented a 8" map of M51. Figure 3 is a 4" resolution map of the inner regions of M51 taken by the Nobeyama Millimeter Array (Tosaki et al. 1990). Note that in all these interferometric maps a large fraction of the single-dish flux (up to 80%) is missing which complicates a lot the interpretation.

The second result is that there is quite detectable CO emission between the arms

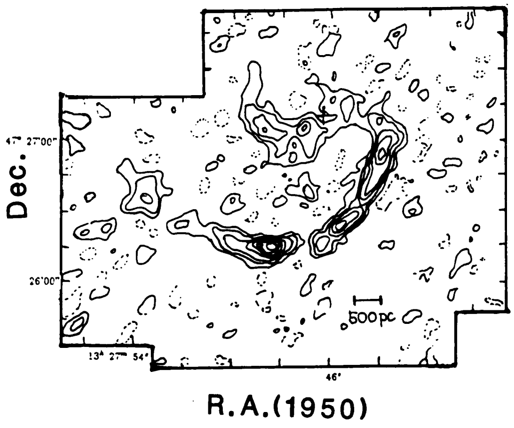

Figure 3 : NMA 4" resolution CO(1-0) map of M51

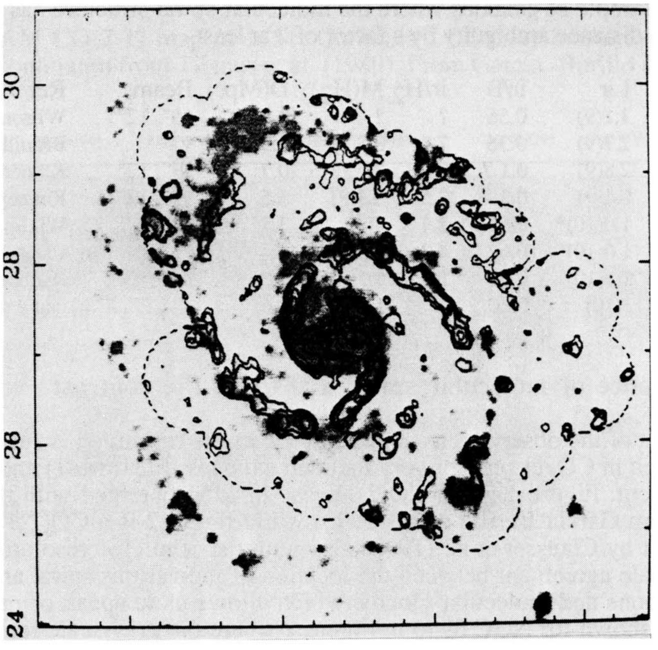

Figure 4 : CO(1-0) map of M51 from the Owens Valley interferometer (Rand & Kulkarni 1990). Note the offset between the CO ridge and the HII regions. CO emission is closely associated with the dust lane

(except maybe in M31). This was already known in our own Galaxy, and yields an arm-interarm contrast that is about 4-6 in the galaxies where it is possible to derive it with confidence (i.e., single-dish observations with enough resolution). The contrast is probably slightly higher in M81 and M31, which suggests that CO-faint galaxies have more contrasted spiral structure. The contrast values are similar in CO(1-0) and CO(2-1) (NGC6946, M51), and there may be an increase of the contrast with radius in M51, as in the Milky Way.

The contrast values are then larger in CO than in the red band and the HI (in NGC 6946, contrasts of 2 when the CO has a contrast of 4, see Casoli et al., 1990) but but pure orbit crowding cannot be excluded : the simulations of Roberts and Stewart (1987) have shown that in this case, molecular contrasts of 4 to 8 can be expected. Thus, it is only in the case of M31 that it seems there is creation of molecular clouds from the atomic gas at the spiral arm crossing (but see the talk by Kutner, this Symposium).

3. Location of the arm tracers

What we call arm tracers are the dust lane (assumed to represent the shock location and the place where the gas enters the arm), the ridges of continuum emission, of HI emission, the HII regions, and also the molecular clouds. The relative location of the arm tracers differs from one galaxy to another, and even inside a single galaxy. In the NW arm of M51, the CO emission mapped by the Owens Valley intereferometer (Rand & Kulkarni 1990, figure 3) is associated with the dust lane and the ridge of non-thermal emission, while the HI ridge and the HII regions are downstream. The 5"-10" offset corresponds to 250 to 500 pc. The association of CO with the shock has been nicely interpreted as evidence for the formation of Giant Molecular Associations in the spiral shock, while the offset could be due to delayed star formation. In this picture, the HI is produced by the dissociation of the molecular clouds by star formation.

However this beautiful pictures fits in only some regions of M51; moreover it is wrong in most other galaxies ! In NGC 6946, there is a very close association of CO maxima, HI and HII regions (see figure 2). In one arm of the barred galaxy M83, the CO emission is offset from the dust lane and associated with the HI and Hβ emission ridges as shown in figure 4 (Wiklind et al. 1990). Similarly, in M81 CO and other arm tracers generally lie downstream of the dust lane, although there is no close association of H_2, HI and giant HII regions (Brouillet et al., 1990).

Some of the differences between these galaxies may be due to the strength of the density-wave : M51 clearly contains a strong density-wave due to the close interaction with the small companion NGC 5195. This is not the whole story since all spiral arms of M51 do not not show the same behavior. In addition M83 probably hosts a strong DW but molecular clouds seem to form downstream.

Another important parameter is the location of the resonances. The spiral arms of M51 lie within the corotation, while in M83 and NGC 6946 the corotation could be at the end of the bar, thus the spiral structure would be between the corotation and the Outer Linblad Resonance.

It is clear that a lot of work remains to be done to quantify the strength of the DW in all these galaxies and to identify the resonances. A promising approach seems to model the behavior of the molecular clouds in the galactic potential (for M51, see a first step by Garcia-Burillo et al., this Symposium). Finally, it has to be noted that *part* of the offset noted above for M51 may be due to missing flux in the interferometric maps : the offset is present but less prominent in the single-dish maps of Garcia-Burillo et al. (1990) as well as in the interferometric maps when short spacings are included (see Lo, this Symposium).

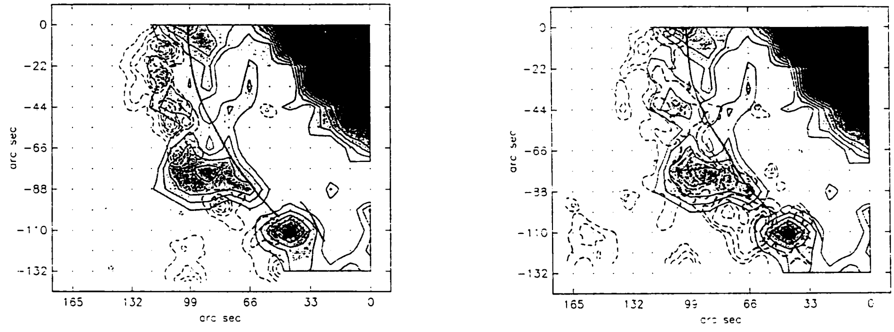

Figure 5 : CO(2-1) emission in M83, from the SEST (Wiklind et al. 1990). Grey-scale and full line ontours present the CO emission, the straight line is the dust lane. Left : dashed line is HI emission, Right : dashed line is Hβ emission

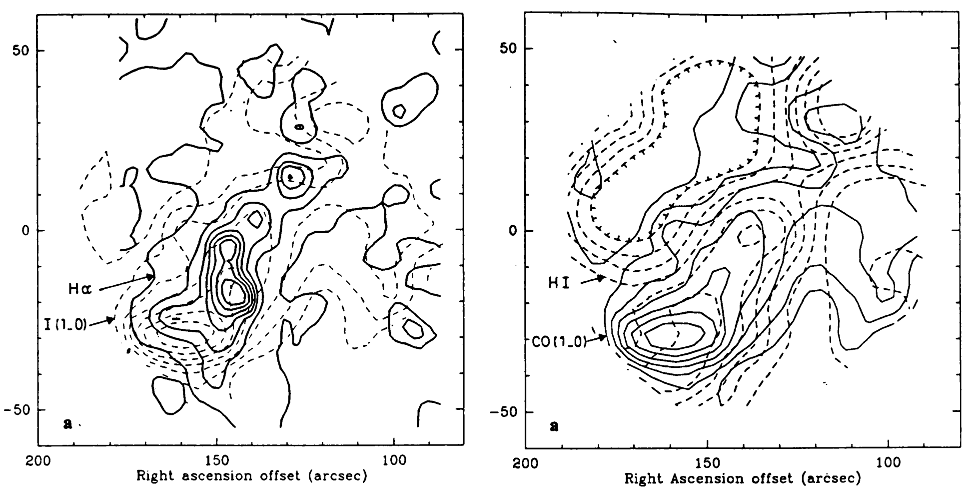

Figure 6 : example of a gaseous supercloud in NGC 6946. Left : dashed is HI emission, full-line contours are CO(2-1). Right : CO is dashed while the full-line contours are the Hα emission. Note the close association of these spiral arm tracers

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4. The nature of arm and interarm clouds

In the arms of M51 and NGC 6946, large molecular complexes have been identified with typical H_2 masses of the order of 10^7 M_o. In NGC 6946, one such complex has been mapped with the IRAM 30m telescope (Casoli et al., 1990). It is associated with a maximum of HI couumn density (figure 6) and a giant HII region. With a typical size of 500 pc, it contains 5 10^7 M_o of H_2, 2 10^7 M_o of HI and a non-negligible amount of ionized gas (10^7 M_o). This is reminiscent of the "superclouds" identified by Elmegreen (1987) in our Galaxy and that would be the building blocks of star formation in many external galaxies.

About 20 Giant Molecular Associations have been identified in M51 (Rand and Kulkarni 1990) with H_2 masses between 1 and 5 10^7 M_o. They are in virial equilibrium but they are not associated with HI maxima (see previous Section) so that here one cannot speak of superclouds.

In NGC 6946 and M51, the molecular gas associated with the arms is not very excited since the average CO(2-1)/CO(1-0) main-beam temperature ration is 0.5-0.6 when smoothed to the same angular resolution. This points towards a CO emission dominated by low-density cloud envelopes. In the nuclei of the two galaxies this ratio is about 1.

Interarm GMAs do exist in M51 (Rand and Kulkarni 1990) but are seen neither in NGC 6946 (with a detection limit of about 10^6 M_o) nor in M83. In these two galaxies the interarm CO emission seems then to originate in small molecular clouds or even in a molecular background. In NGC 6946 the interarm CO(2-1)/CO(1-0) ratio is also about 0.5 while in the arm of M83 that has been observed by Wiklind et al. (1990) it is about 1.8, while it is 1 in the arm and nucleus. This may be the signature of partly optically thin gas.

5. Streaming motions

Streaming motions are believed to be the best evidence for the presence of a density wave. Observationally, perturbations in the radial velocity Vr are better seen on the minor axis (with the problem that one has to know the orientation of the galaxy) while perturbations in $V\theta$ are observed on the major axis.

What does the density-wave theory predict ? At the spiral arm crossing before the corotation CR Vr is negative corresponding to an inward motion and smoothly returns to 0 in the interarm. Before the arm $V\theta$ should be negative and positive after (i.e. higher than rotational).

What is observed ? In M51 the observed perturbations in CO (e.g. Rydbeck et al. 1986, Rand and Kulkarni 1990) are consistent with that picture ; the velocity perturbations are as high as 20 to 30 km/s (50 km/s in the plane of the galaxy). Such strong perturbations are the signature of a very strong wave.

On the other hand, in NGC 6946 all the CO is observed at the normal rotational velocities and it is the HI which is at peculiar velocities ! In the NE arm which is almost on the major axis, at the arm crossing CO and HI are at normal velocities ; downstream there is few CO but still some HI at -15 km/s tangential velocity (this corresponds to an in-plane velocity of 30 km/s, thus not as high as in M51 although still important). In the outer N arm, close to the minor axis, HI is seen at Vrad = +20 km/s. (CO has not been observed). This is consistent with the theory if this is the far side. In M81 also the CO is at the normal rotational velocities while velocity perturbations consistent with the DW theory are seen in HI.

Finally, in M31, velocity perturbations have been seen in the minor axis (Sandqvist et al. 1989) : in the region that they have observed the radial motion is outwards, which can be interpreted in the DW theory if the observed region is outside CR.

Studying velocity perturbations reveals then of great importance for showing the presence of a DW in a galaxy and for quantifying the strength of this wave. Furthermore, it may help identifying the location of the resonances.

6. Density wave, HI, GMC and star formation

None of the observed contrasts are high enough to exclude that even the GMAs are not just cloud aggregations in the spiral arm. In some regions of M51 a probable sequence leading to star formation is the following :

• spiral shock -> molecular complex formation from small clouds -> star formation -> cloud dissociation -> formation of small molecular clouds and of HI.

In M31 a completely different mechanism seems to operate :

• spiral "shock" -> H_2 formation inside HI -> star formation,

but all intermediate sequences seem to be possible, even in the same galaxy, and this not obviously related to the DW strength (see M81).

Another point of importance is that the presence of a DW does not guarantee a large molecular content. Indeed Stark et al. (1987) have shown that grand-design spirals have the same CO content as flocculent ones (see also Knezek et al., 1990). Galaxies with a low gas surface density and a strong wave, such as M81 and probably M31, do not succeed in forming lots of H_2 out of their atomic gas and have in their inner regions only 20% of H_2, while gas-rich DW spirals such as NGC 6946 and M51 have 80% of H_2.

Thus, DW do not help galaxies in forming more molecular clouds. Even more, they are not necessary for star formation : stars form in irregulars, lenticulars as well as in flocculent galaxies ; and they do not help to form more stars on a global scale : the FCRAO extragalacticv survey has shown that flocculent spirals have a higher star formation efficiency, as measured by the L_{IR}/M(H2) ratio, than the grand-design ones ! All of this suggests that on the average density waves merely organize the interstellar matter of galaxies. In this respect, galaxy interactions such as mergers seem to be much more efficient for an enhanced star forming activity.

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