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Molecular gas and star formation in the Milky Way

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Abstract. The dense molecular gas is the ideal tracer of the spiral structure in the Milky Way, and should be used intensively to solve the puzzle of its structure. In spite of our position inside the plane, we can hope to disentangle the structures, with position-velocity diagrams, in addition to $(l - b)$. I summarize the state of the art simulations of gas flows in the MW, and describe what can be done to improve the models, taking into account the star formation, in view of what is already done in external galaxies, with a more favorable viewing angle.

1. THE IMPORTANCE OF THE GAS

In the near future, GAIA will make a breakthrough in our knowledge of the stellar component of our Galaxy and its dynamics. But the knowledge in its gas component may not progress as much. Reproducing the gaseous spiral structure of our Galaxy is a difficult enterprise, given our internal position. Distances of the various features or objects are derived through a kinematical model, with near-far ambiguities inside the solar circle. The first deprojections of the Galactic plane in the atomic gas observed at 21cm (Oort et al. 1958 [21]) had only a very sketchy and approximative spiral morphology, without identifying the actual arms, and their continuity. One of the first successful models was that from Georgelin & Georgelin (1976) [14] of four tightly-wound arms, traced by OB associations, optical or radio HII regions, or molecular clouds. As in other galaxies, the spiral structure is better contrasted in the gas, atomic (HI, Liszt & Burton 1980 [16]) and molecular (CO surveys, Dame et al 2001 [9]), because of its low velocity dispersion, and its confinement to the plane.

Position-velocity (P-V) diagrams are particularly instructive, revealing the high velocity (∼560 km/s) Central Molecular Zone (CMZ) near zero longitude, with a molecular ring, connecting arm, 3 kpc arm, etc. (cf Figure 1). The existence of a bar has long been suspected from non-circular motions towards the center, and has been directly confirmed by COBE and 2MASS (e.g. Lopez-Corredoira et al 2005 [17]). Near-infrared images show clearly the peanut bulge, which is thought to be formed through vertical resonance with the bar (e.g. Combes et al 1990 [8]). The CMZ has a peculiar parallelogram shape in P-V diagram (Bally et al 1988 [3]), that has been first interpreted in terms of cusped x1 and almost circular x2 periodic orbits, and associated gas flows, by Binney et al (1991) [4]. Then Fux (1999) [13] carried out fully self-consistent N-body and hydrodynamical simulations of stars and gas to form a barred spiral, and fit the Milky Way. He succeeded remarkably to reproduce the HI and CO P-V diagrams with a bar pattern speed of about 40 km/s/kpc, implying a corotation at 5 kpc, and an ILR producing the x2 orbit inside 1 kpc radius. The spiral structure has essentially 2 arms starting at the end of the bar.

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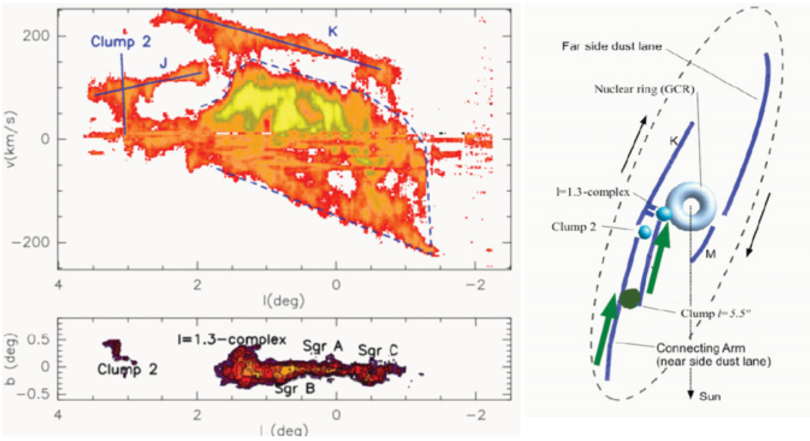

Figure 1. Left Longitude-velocity diagram of the CO(1-0) emission in the CMZ (Central Molecular Zone, Bally et al 1988 [3]). Some remarkable features are underlined, as Clump2, or strucrures K, J (Rodriguez-Fernandez et al 2006 [24]). At the bottom is the integrated intensity map. **Right** Schematic reconstruction in the galactic plane of some of the remarkable structures, inside the delineated bar (Rodriguez-Fernandez & Combes 2008 [25]).

2. SEVERAL POSSIBLE MODELS

More recently, new efforts to reconstitute the spiral structure in the galactic plane have been attempted in the HI gas (Levine et al 2006 [15]), and in the CO gas (Nakanishi & Sofue 2006 [19], Englmaier et al 2009 [12]). The best fit could be two arms, starting at the end of the bar, with a pitch angle of 12°, although four arms are still possible. Pohl et al (2008) [22] have tried novel deprojections, by simulating the gas flow with SPH in a bar potential, and obtaining distances with a kinematical model derived from the non-circular velocity field obtained. A test of the procedure with a 2 arms+bar fiducial model, with only one pattern speed, retrieves after deprojection a four arms spiral.

It is frequent in external galaxies (and in simulations) that several pattern speeds develop in a disk, and in particular the spiral could rotate slower than the bar. This has been explored by Bissantz et al (2003) [5], who find as a best fit Ω_p= 60 km/s/kpc and 20 km/s/kpc for the bar and spiral respectively. They simulate gas flows in a fixed potential, and find that fixing the spiral potential in addition to the bar gives better fits.

In the 2MASS stellar counts, a nuclear bar has been found by Alard (2001) [1], and a CO nuclear bar corresponds (Sawada et al 2004 [28]). New simulations of gas flow in a two-bar models have been done by Rodriguez-Fernandez & Combes (2008) [25], who find a best fit when the two bars are nearly perpendicular, and the bar-spiral pattern is about 35 km/s/kpc (similar to Fux, 1999 [13]). The model shows the far-side symmetric of the 3 kpc arm, which has just been discovered in the CO P-V diagram (Dame & Thaddeus 2008 [10]). It reproduces also the connecting arm (characteristic leading dust lanes along the bar, fig 1). No evidence is found of lopsidedness in the stellar potential, and the CO lopsidedness must be a purely gaseous phenomenon. Other prominent features have not yet been interpreted, such as the warp or tilt of the nuclear gas structure. Baba et al (2010) [2] have included in their model of the Milky Way more detailed physics, in particular the multi-phase interstellar medium, its self-gravity, star-formation and supernovae feedback. This allows them to reproduce the clumpy morphology observed in the P-V diagrams of CO emission.

It is interesting to note that the Galaxy is finally more symmetric than previously thought. Dame et al (2011) [11] have discovered through CO emission a spiral feature in the distant outer Galaxy in the first quadrant, as a continuation of the Scutum-Centaurus arm.

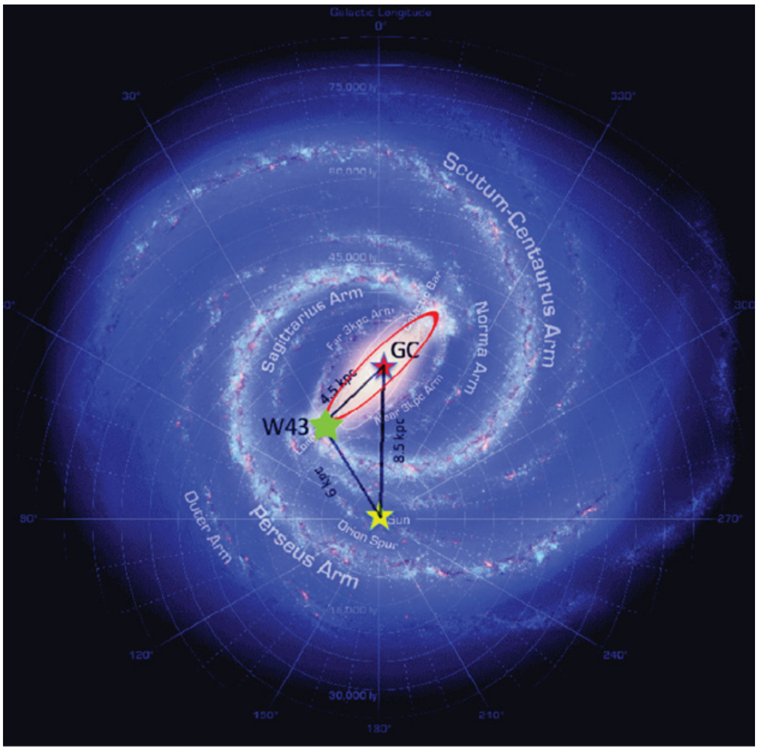

Figure 2. Artist view of the Milky Way with the long bar outlined by a red ellipse (Churchwell et al. 2009). W43 is located at the extremity of the bar. From Nguyen-Luong et al (2011) [20].

3. MASERS AND STAR FORMATION

A very performant method to determine precisely the distances has been exploited recently: the 12 GHz methanol masers associated to High Mass Star Formation Regions (HMSFR), and their trigonometric parallax determined from VLBI (see e.g. the Bessel survey, Brunthaler et al 2011 [6]). A spectacular example has been studied toward the HMSFR G9.62+0.20 by Sanna et al (2009) [27]. They determine a distance of D= 5.2 $\pm$0.6 kpc, while with a LSR velocity of 2 km/s, the kinematical distances are 0.5 and 16 kpc! The region has a large non-circular motion, composed of a radial peculiar velocity of 41 km/s outward, and an azimuthal counter-rotation of 60 km/s. When considering that the G9.62+0.20 massive star forming region is part of the near side 3 kpc arm, then the kinematic peculiarites are easily explained with the bar.

Reid et al (2009) [23] combined the trigonometric parallaxes and the proper motions of the HMSFR masers to determine the morphology of local spiral arms, and their pitch angle. They find that star-forming regions on average are orbiting the Galaxy with a lag of 15 km/s with respect to circular orbits (17 km/s for 6.7 GHz masers, Rygl et al 2010 [26]). Kinematic distance are sometimes wrong by a factor 2. The scatter of HMSFR locations within the arm is larger than parallax errors, and limit the determination of the arm pitch angles. The data are precise enough to imply a redetermination of galactic main parameters, solar radius or velocity (McMillan & Binney 2010 [18], Schoenrich et al 2010 [29]).

From large-scale surveys of gas emission (HI, CO) but also dust at many wavelegnths, it is possible to identify star formation regions, and their location in the spiral structure morphology. Nguyen-Luong et al (2011) [20] have identified W43 as a large ($\sim$140 pc) and coherent complex of molecular clouds that is surrounded by an atomic gas envelope ($\sim$290 pc). W43 is particularly massive (7 10^6 $M_\odot$) and concentrated. Its position is conspicuous, at the end of the bar, where spiral arms begin to wind out (cf Figure 2). HII Regions are frequently located there in barred galaxies, at the crossing of several orbital streams. Its star formation rate is up to 0.1 $M_\odot$/yr, and its star formation efficiency SFE= 25%/Myr.

4. CONCLUSIONS

For the gaseous medium, it is presently still difficult to disentangle distances and dynamical effects. While stellar dynamics will make considerable progress with GAIA, we need the distances and proper motions in the interstellar medium. The high mass star formation masers method, determination of parallaxes and propoer motions with VLBI, is highly promising.

The spiral structure of our Galaxy has the largest contrast in the gas. The number of arms and their precise locations are not yet solved, the spiral structure might include branchings and harmonics, and be more complex than the stellar one, with two arms and a bar. The central structure (central molecular zone) is lopsided, and may be tilted and warped. The structure should be studied in more details, and could be the consequence of gas accretion. The number of patterns, and their respective pattern speeds, is still not well known territory. From near-infrared surveys, it is likely that a secondary bar is embedded in the primary bar.

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