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M51: Molecular Spiral Arms, GMAs and Superclouds

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Abstract. We present an aperture synthesis image of M51 in the CO 1 → 0 line at 9" × 7" resolution made with the Owens Valley Millimeter Interferometer. The image is a mosaic of 30 one-arcminute fields. The image shows narrow spiral arms which are coincident with the optical dust lanes and non-thermal radio emission, but are offset from the ridges of Hα emission. Many dense concentrations of CO emission, termed Giant Molecular Associations (GMAs), are seen both along and between the arms. The typical GMA mass is about 3×10^7 $M_\odot$. Most of the on-arm GMAs appear to be gravitationally bound. These GMAs consist of several spectral components ("Molecular Superclouds") with typical mass 10^7 $M_\odot$, which also appear to be bound. The observed streaming motions in the GMAs are consistent with density wave theory. The interarm GMAs are not gravitationally bound, and are likely to be due to a secondary compression of the density wave.

I. Introduction. While it is generally acknowledged that density waves are responsible for galactic spiral structure, their role in triggering coherent star formation remains obscure. Direct evidence for the existence of density waves has been provided by the detection of gas streaming motions in the grand-design spiral galaxies M51 (Tully 1974; Rydbeck *et al.* 1985) and M81 (Visser 1980). However, the global data on spirals seems to indicate that density waves have little to do with star formation (Elmegreen 1987a).

Because very little is understood about the relationship between density waves and star formation, we have undertaken a major program of radio synthesis mapping of M51 (NGC 5194) in the 2.6 mm CO 1 → 0 transition with the Owens Valley Millimeter Interferometer. Initial results for 8 one-arcminute fields revealed narrow molecular spiral arms and demonstrated the existence of spatially resolved velocity shifts across the arms in the NW quadrant of the galaxy (Vogel, Kulkarni, and Scoville 1988, hereafter VKS) in the sense predicted by density wave theory. The SFE was found to be higher in the arms than between the arms (VKS; Rand and Kulkarni 1989).

II. Results. The final product of our 3 year study is the mosaic of 30 one-arcminute fields shown in Figure 1. The resolution is 9" × 7", and the primary beam of each field is 65". Two arms of width 10" – 20" can be traced for about 270° of azimuth. The emission breaks up into discrete features along these arms, while disconnected emission features delineate spiral arms further from the nucleus. Discrete features are also seen between the arms. We detect typically 25 – 35% of the flux contained within a single-dish beam at a given position (Lord 1987).

An overlay of the CO map with an Hα CCD image (not shown) shows that the molecular arms are offset by 5"–10" to the inside of the Hα ridge in the inner regions, implying a delay between the peak compression of the molecular gas and the peak of massive star formation of $\sim 10^7$ years. A similar offset is seen between the dust lanes and thermal radio emission (Tilanus and Allen 1989). An overlay of our map with a red-continuum CCD image (not shown) shows an excellent correspondence of the molecular arms and the dust lanes.

The molecular emission shows dense concentrations of gas, which we call GMAs, both on and between the arms. We derive masses of $10^7 - 6 \times 10^7$ $M_\odot$ for the on-arm GMAs and $10^7 - 4 \times 10^7$ $M_\odot$ for the interarm ones. Thus their masses are more than an order of magnitude greater than those of typical Galactic GMCs ($10^5 - 10^6$ $M_\odot$). We identify 28 GMAs in our map: 20 on the arms, and 8 between the arms.

a) On-arm GMAs. From a comparison of virial and flux-based masses, we find that most of the on-arm GMAs are gravitationally bound. A simple simulation shows that they cannot simply be explained as a chance superposition of a few large GMCs because the required on-arm surface density for this is much higher than observed. These GMAs are also probably tidally stable while on the arms, but may become unstable when they leave the arms. Spectra of the on-arm GMAs show that they are dominated by a few (1 to 4) velocity components, with typical mass $\sim 10^7$ $M_\odot$. A comparison of the virial and flux-based masses of these spectral components indicates that they are probably gravitationally bound.

The GMAs and their constituent Superclouds may be extreme cases of agglomeration through cloud-cloud collisions – a process which is expected to be more effective in assembling such high-mass clouds in M51 than in our Galaxy. Cloud-cloud collisions have been proposed as a mechanism for massive star formation in our Galaxy (Scoville *et al* 1986). In this scenario the massive star formation rate depends on the square of the local molecular cloud density. This process could therefore also explain the higher SFE seen on the arms in M51. Alternatively, such high mass clouds may form directly through gravitational instability, which is enhanced in the arms (Elmegreen 1987b).

b) Streaming motions in on-arm GMAs. In the narrow region of spiral phase where the gas is highly compressed, the density wave is predicted to disturb the basic circular rotation of the gas by causing a positive shift in the tangential velocity in the direction of rotation and a shift in radial velocity toward the nucleus. One of the most important results of VKS was the detection of such tangential and radial "streaming motions" in two GMAs near the major and minor axes, respectively, in the directions predicted by the models. With the now more complete data, streaming motions are detected in 4 additional complexes. In each case, the velocity shift is in the direction predicted by density wave theory.

c) Interarm GMAs. The interarm GMAs have a mean mass of 1.5×10^7 $M_\odot$ and show on average 3 or 4 distinct spectral components with a mean mass of 4×10^6 $M_\odot$. The virial masses of these GMAs are much greater than their flux-based masses. A simulation shows that they cannot all be explained as simple random superpositions of a few GMCs – the more massive ones must have a dynamical origin. A possible explanation is that they are formed by secondary compressions of the density wave. If this were the case, then we should expect to see streaming motions in these GMAs. The two interarm GMAs near the major and minor axes do indeed show tangential and radial velocity shifts in the sense predicted by density wave theory. In support of this interpretation is the fact that we see faint, narrow strings of HII regions giving the appearance of coherent spiral features in the NE and SW interarm regions near concentrations of interarm GMAs, indicating a large-scale, but relatively low-level, star forming event. All the evidence therefore indicates that these GMAs are indeed formed by secondary compressions of the density wave.

III. References

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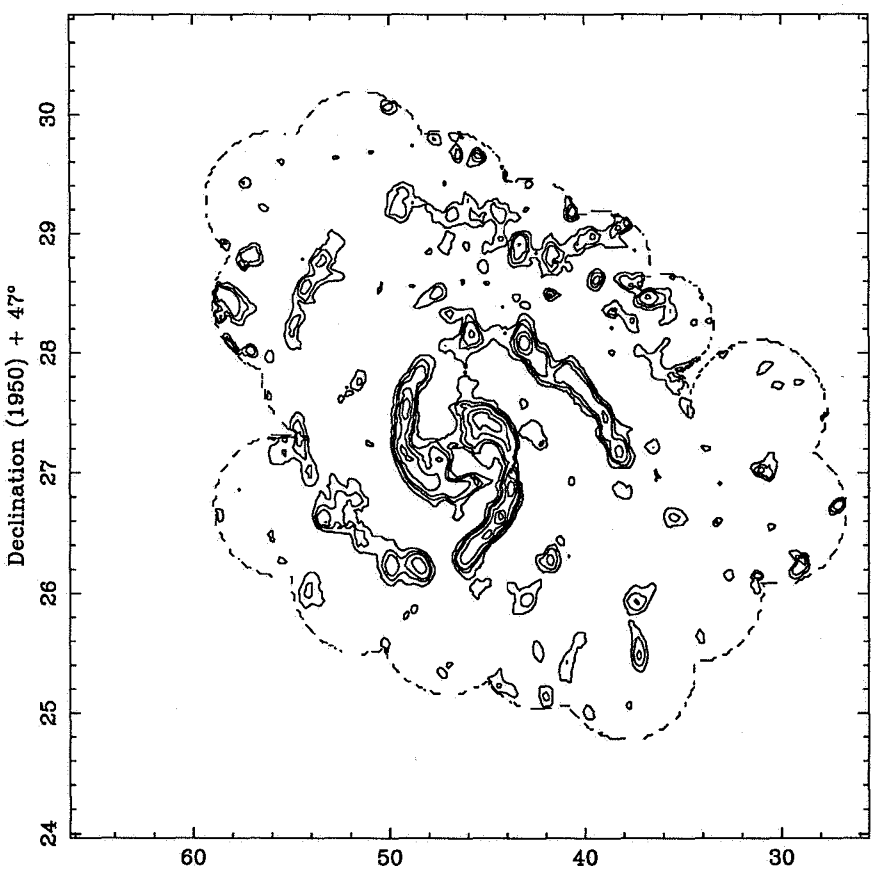

Fig. 1. Mosaic map of CO emission in M51. The mapped region is outlined by the dashed curve. No data from beyond the half-power point of the primary beam are included in the mosaic. Due to improvements in receiver sensitivity and atmospheric conditions over the three year span of the observations, there is a variation in rms noise of a factor of two over the mosaic. Sensitivity generally improves from NW to SE in the map, ranging from about 2 Jy km s^{-1} $beam^{-1}$ to 4 Jy km s^{-1} $beam^{-1}$. The lowest contour is 2.2 Jy km s^{-1} $beam^{-1}$ and the interval is 4.5 Jy km s^{-1} $beam^{-1}$.