The Astrophysical Journal, 700:L132–L136, 2009 August 1 doi:10.1088/0004-637X/700/2/L132

DYNAMICALLY DRIVEN EVOLUTION OF THE INTERSTELLAR MEDIUM IN M51

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Received 2009 March 30; accepted 2009 June 30; published 2009 July 13

ABSTRACT

Massive star formation occurs in giant molecular clouds (GMCs); an understanding of the evolution of GMCs is a prerequisite to develop theories of star formation and galaxy evolution. We report the highest-fidelity observations of the grand-design spiral galaxy M51 in carbon monoxide (CO) emission, revealing the evolution of GMCs vis-a-vis the large-scale galactic structure and dynamics. The most massive GMCs (giant molecular associations (GMAs)) are first assembled and then broken up as the gas flow through the spiral arms. The GMAs and their H_2 molecules are not fully dissociated into atomic gas as predicted in stellar feedback scenarios, but are fragmented into smaller GMCs upon leaving the spiral arms. The remnants of GMAs are detected as the chains of GMCs that emerge from the spiral arms into interarm regions. The kinematic shear within the spiral arms is sufficient to unbind the GMAs against self-gravity. We conclude that the evolution of GMCs is driven by large-scale galactic dynamics—their coagulation into GMAs is due to spiral arm streaming motions upon entering the arms, followed by fragmentation due to shear as they leave the arms on the downstream side. In M51, the majority of the gas remains molecular from arm entry through the interarm region and into the next spiral arm passage.

Key words: galaxies: individual (NGC5194, M51) – ISM: clouds – ISM: evolution

1. INTRODUCTION

Despite numerous studies of molecular gas in the Milky Way and galaxies (Scoville & Sanders 1987; Blitz et al. 2007), the processes affecting evolution of giant molecular clouds (GMCs) have remained poorly understood. In fact, uncertainty remains as to whether GMCs are stable structures that survive over a galactic rotation period ($> 10^8$ yr; Scoville & Hersh 1979; Scoville & Wilson 2004) or are transient structures, destroyed immediately after formation by violent feedback from young stars (a few $\times 10^7$ yr; Blitz & Shu 1980; Elmegreen 2007, or even shorter $\sim 10^6$ yr; Elmegreen 2000; Hartmann et al. 2001).

The internal structure of GMCs is generally believed to be determined by an approximate balance of self-gravity and internal turbulent or magnetoturbulent pressures (exceeding the external interstellar medium (ISM) pressures by 2 orders of magnitude; Myers 1978). Therefore, GMCs are likely self-gravitationally bound, distinct, and long-lived objects (Scoville & Sanders 1987). A difficulty, however, arises in maintaining the internal turbulence over the long lifetimes, since the turbulence should dissipate rapidly within a cloud crossing time ($\sim$a few $\times 10^6$ yr). The energy must be continuously resupplied if their lifetimes are longer (e.g., Heitsch et al. 2001). The energy source is still unknown although supernovae and galactic rotation have been suggested (Mac Low & Klessen 2004; Wada et al. 2002; Koda et al. 2006). Models for rapid GMC formation and disruption have been proposed to avoid the need to re-energize the turbulence (Ballesteros-Paredes et al. 1999). The absence of older > 5 Myr stellar populations within GMCs has been cited as evidence of short GMC lifetimes (Hartmann et al. 2001). However, more recent observations do find some older star populations (Jeffries 2007; Gandolfi et al. 2008; Oliveira et al. 2009), presumably indicating longer lifetimes. Moreover, at some point the older stars must drift free of the GMCs since they are no longer subject to the hydrodynamic forces of the ISM gas. The collapse timescale of star-forming cores via ambipolar diffusion is substantial, and may support the longevity (Tassis & Mouschovias 2004).

This controversy carries over when considering the galactic spatial distribution of GMCs, since early molecular line surveys of the Milky Way linked the GMC evolution to the Galactic disk dynamics. Cohen et al. (1980) argued that GMCs were confined largely to the spiral arms with very few seen in the interarm regions, implying that GMCs must be short lived with a lifetime similar to the arm-crossing timescale (a few $\times 10^7$ yr; Dame et al. 2001). However, Sanders et al. (1985) claimed to find many GMCs in the interarm regions, suggesting that the GMCs must be quasi-permanent structures, surviving $\gtrsim 10^8$ yr, i.e., a substantial fraction of a galactic rotation period. A recent ^{13}CO survey suggests that GMCs in the interarm regions are less massive (Koda et al. 2006; Jackson et al. 2006), accounting for the earlier discrepancies if the Cohen et al. survey missed the less-massive interarm GMCs. In any case, all Galactic surveys have the intrinsic limitation that the velocity dispersion and streaming motions of the clouds can blur out the spiral arm/interarm definition when the disk is viewed edge-on.

High-resolution molecular gas observations of external face-on spiral galaxies are therefore essential for the full census of

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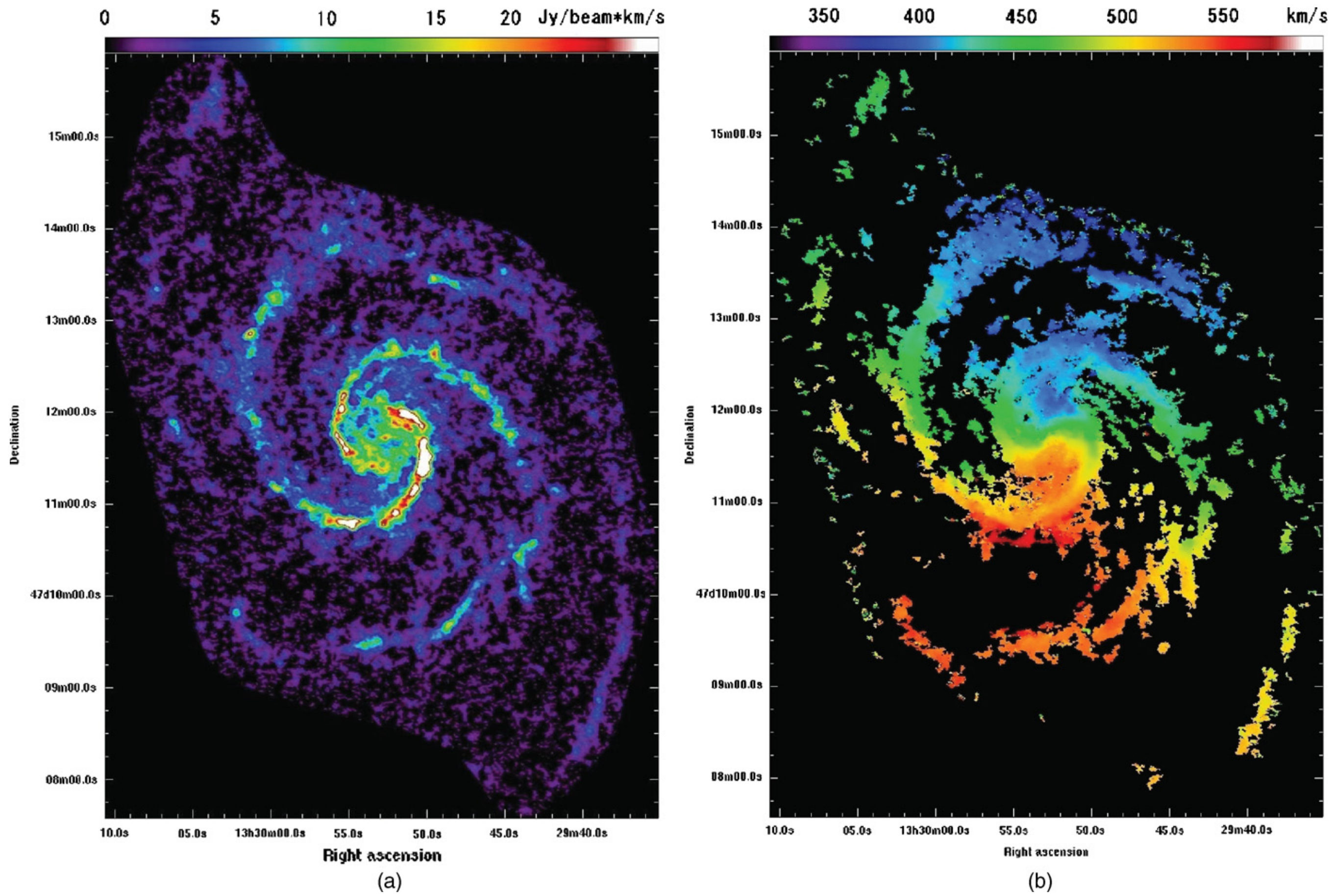


Figure 1. (a) Integrated intensity map of CO(J = 1–0) emission of the entire disk of M51. The 6′.0 × 8′.4 region was mosaiced in 151 pointings at 4″ resolution with the CARMA interferometer. The total power and short-spacing data are obtained with the On-The-Fly mapping mode of the BEARS multi-beam receiver on the Nobeyama Radio Observatory 45 m telescope (NRO45). The CARMA and NRO45 data are combined in the Fourier space. The maps clearly detect GMCs over the entire disk for the first time, including both the prominent spiral arms and interarm regions. (b) Velocity field. Significant shear motions are seen at tangential positions (P.A. of the disk kinematic major axis is −11 deg).

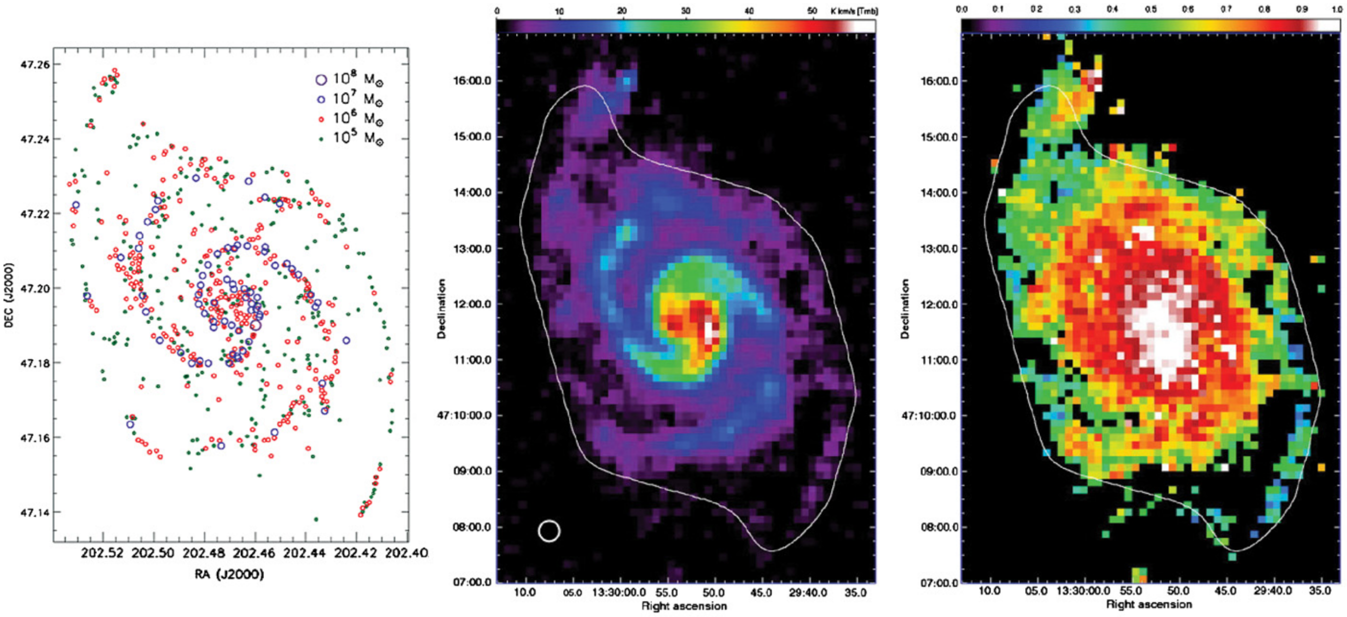
GMC population over galactic disks. However, prior interferometers, which are required for such high-resolution imaging, had only a small number of telescopes, and thus were severely limited by low image fidelity. Indeed, the high side lobes of bright spiral arms due to poor uv-coverage have often led to false structures in the interarm regions (Rand & Kulkarni 1990; Aalto et al. 1999; Helfer et al. 2003).

2. OBSERVATIONS AND DATA REDUCTION

High-fidelity imaging of nearby galaxies at millimeter wavelengths has now become feasible with the Combined Array for Research in Millimeter Astronomy (CARMA). CARMA is a new interferometer, combining the six 10 m antennas of the Owens Valley Radio Observatory (OVRO) millimeter interferometer and the nine 6 m antennas of the Berkeley–Illinois–Maryland Association (BIMA) interferometer. The increase to 105 baselines (from 15 and 45, respectively) enables the highest-fidelity imaging ever achieved at millimeter wavelengths. The entire optical disk of the Whirlpool galaxy M51 (6′.0 × 8′.4) was mosaiced in 151 pointings with Nyquist sampling of the 10 m antenna beam (FWHM of 1 arcmin for the 115 GHz CO J = 1–0 line). The data were reduced and calibrated using the Multichannel Image Reconstruction, Image Analysis, and Display (MIRIAD) software package (Sault et al. 1995).

We also obtained total power and short-spacing data with the 25-Beam Array Receiver System (BEARS) on the Nobeyama Radio Observatory 45 m telescope (NRO45, FWHM = 15″). Using the On-The-Fly observing mode (Sawada et al. 2008), the data were oversampled on a 5″ lattice and then re-gridded with a spheroidal smoothing function, resulting in a final resolution of 22″. We used the NOSTAR data reduction package developed at the Nobeyama observatory. We constructed visibilities by deconvolving the NRO45 maps with the beam function (i.e., a convolution of the 15″ Gaussian and spheroidal function), and Fourier transforming them to the uv-space. We combined the CARMA and NRO45 data in Fourier space, inverted the uv data using theoretical noise and uniform weighting, and CLEANed the maps to yield a three-dimensional image cube (right ascension, declination, and LSR Doppler velocity).

The combined data have an rms sensitivity of 40 mJy beam^{-1} in 5.1 km s^{-1} wide channels, corresponding to $1 \times 10^5 M_\odot$ at the distance of 8.2 Mpc (adopting a CO-to-H_2 conversion factor of $X_{CO} = 2 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$). Typical GMCs in the Milky Way (i.e., $4 \times 10^5 M_\odot$ in mass and 40 pc in diameter; Scoville & Sanders 1987) are therefore detected at 4σ significance. Our angular resolution of 4″ corresponds to 160 pc, which is high enough to isolate (but not resolve) the GMCs, given that the typical separation of Galactic GMCs is a few 100 pc to kpc (Scoville & Sanders 1987; Koda et al. 2006). The combination of spatial resolution, sensitivity, and image fidelity differentiates our study from previous work (Vogel et al. 1988; Garcia-Burillo et al. 1993; Nakai et al. 1994; Aalto et al.



(a) (b) (c)

Figure 2. (a) Distribution of GMCs (10^{5-6} $M_\odot$) and giant molecular associations (GMAs; $> 10^7$ $M_\odot$) in M51. The GMCs/GMAs are identified with the CLUMPFIND algorithm (Williams et al. 1994), down to 4σ significance, corresponding to the typical GMC mass in the Milky Way (4×10^5 $M_\odot$; Scoville & Sanders 1987). The small green circles includes only the GMCs with mass above 4×10^5 $M_\odot$. The GMAs are seen only in the spiral arms, suggesting that they are assembled and broken up as the gas flows through the spiral arms. Numerous GMCs are still seen in the interarm regions, indicating that they survive while crossing the interarm regions. (b) Nobeyama 45 m telescope CO(J = 1–0) map. The circle at the lower-left corner is the 22″ beam. The white contour around the emission indicates roughly the coverage of CARMA observations. (c) Molecular gas fraction defined as $2n_{\mathrm{H_2}}/(n_{\mathrm{H}} + 2n_{\mathrm{H_2}})$, calculated with H I data from Braun et al. (2007). The fraction is high within the major part of the disk and does not change azimuthally, indicating that the gas stays molecular over a revolution.

1999; Helfer et al. 2003), and enables a reliable census of GMCs in M51.

Figure 1(a) shows the CO map integrated over all velocities. The new image shows the full distribution of molecular gas over the entire optical disk of M51 (14.3×20.0 kpc^2), including both the prominent spiral arms and interarm regions. The bright inner arms have been previously imaged (Vogel et al. 1988; Aalto et al. 1999), but the new data extend these arms over the full disk and most importantly, yield significant detection of interarm GMCs for the first time. Figure 2(a) shows the distribution of discrete GMCs measured using CLUMPFIND (Williams et al. 1994), clearly indicating many GMCs with mass exceeding 4×10^5 $M_\odot$ in the interarm regions. Lower mass GMCs would not be detected by the cloud finding algorithm and only 36% of the interarm CO emission is seen in the detected discrete clouds shown in Figure 2.

3. DISCUSSION

Two possibilities for GMC formation and lifetime can clearly be distinguished from the observed GMC distribution relative to the spiral arms. One possibility is that they are transient, short-lived structures—formed locally at convergence locations of the galactic hydrodynamic flows and destroyed quickly by disruptive feedback from star formation within the GMCs. Alternatively, if the GMCs are long lived, lasting through the interarm crossing period, their presence in the interarm regions is naturally explained. A simple calculation can be done to rule out the formation of abundant GMCs from the ambient gas with a low average density in the interarm regions. Assuming a very ideal spherical gas accretion of the converging velocity v into the volume with the radius r, the mass accumulates within the time t is $M = 4\pi r^2 v m_{\mathrm{H}} n t$, where n is the number density of ambient gas and m_{H} is the mass of hydrogen atom. Using a GMC radius $r \sim 20$ pc, typical velocity dispersion in galactic disk $v \sim 10$ km s^{-1}, and average gas density $n \sim 1$–5 cm^{-3} (inferred for M51 in the areas without GMCs), it takes $\sim 10^8$ yr to accumulate 4×10^5 $M_\odot$. This mass-flow argument is valid even when the ambient gas is not exactly diffuse but consists of smaller clouds if their distribution is roughly uniform. Therefore, the majority of the GMCs in the interarm regions cannot have formed there locally on the required short timescales (i.e., interarm-crossing timescale $\sim 10^8$ yr).

Figure 2(a) also reveals that the molecular gas properties, specifically their masses, are significantly dependent on galactic environment. The most massive structures with 10^{7-8} $M_\odot$, referred to as giant molecular associations (GMAs), are found only in spiral arms, not in interarm regions. The improved image fidelity was necessary to avoid misidentification of even such massive GMAs, especially in the interarm regions. GMAs must therefore form and disrupt while crossing the spiral arms (with a timescale typically ~ 2–5×10^7 yr). Their formation within the arms is aided by the spiral streaming which causes deflection and convergence of the galactic flow streamlines in the arms. Although stellar feedback (e.g., photodissociation by OB star ultraviolet radiation and supernova explosions) is often invoked for GMC destruction (Larson 1988; Williams & McKee 1997), these mechanisms are not a likely cause of significant GMA dissipation given their masses (10^{7-8} $M_\odot$, see Figure 2(a); Williams & McKee 1997). More telling is the high-mass fraction of H_2 in the interarm regions (Figures 2(b) and (c)). Comparing the mean molecular gas surface density with that of the H I (Braun et al. 2007), we estimate that 70%–80% of the gas remains H_2 within the major part of the disk (~ 12 kpc; Figure 2(c)). Thus, GMAs are not significantly dissociated into atomic or ionized gas. We conclude that the GMAs must be fragmented into the less-massive GMCs and the most massive of these are seen as discrete clouds in the interarm regions in

Figure 2(a). Figure 2(a) includes only the GMCs down to the 4σ level; the sum of their emission is 36% of the total emission of the entire disk. The remainder of molecular emission is presumably in less-massive GMCs, not identified as discrete clouds at the current resolution and sensitivity. Their distribution must be roughly uniform in the interarm regions since they are resolved out at 4″ resolution.

It is unlikely that a significant portion of the remaining emission arises in diffuse molecular gas at low densities. First, the critical density for collisional excitation of CO(J = 1–0) transition is a few $\times 100$ cm^{-3} in optically thick clouds, similar to the average density within GMCs in the Milky Way (Scoville & Sanders 1987). The critical density is even higher, ~ 3000 cm^{-3}, in optically thin regions. Thus, CO emission should not be detected if the density is lower than the densities of GMCs. Second, CO molecules rapidly dissociate in the diffuse interstellar radiation field if they are unshielded by a sufficient column of dust. It is often discussed that a visual extinction of only $A_{\rm V} \sim 1$ mag is sufficient for shielding (Pringle et al. 2001); however, this is true only at high densities (10^3 cm^{-3}; van Dishoeck & Black 1988). A higher $A_{\rm V}$ is necessary at lower densities, since the rate of molecular formation must be rapid to counterbalance the rapid dissociation. At the typically densities of a few 10^2 cm^{-3} expected for molecular gas based on Galactic studies, several magnitudes of visual extinction are required and the CO emitting gas must reside in GMC-like structures during passage trough the interarm areas.

Lastly, we address the nature of the GMAs: are they distinct clouds, and simply an extension of GMC mass spectrum, or the confusion of many GMCs concentrated by orbit crowding in the spiral potential but unresolved due to the limited spatial resolution. The gas surface densities within the GMAs are 200–1000 $M_\odot$ pc^{-2}, generally higher than that in Galactic GMCs ($\sim 170\, M_\odot$ pc^{-2}; Solomon et al. 1987). The FWHM thickness of the molecular gas disk in M51 is unknown but in the Galaxy it is ~ 120 pc (Scoville & Sanders 1987), so the average gas densities within the GMAs (40–200 cm^{-3}) are similar to typical GMC densities (Solomon et al. 1987). Thus, the molecular gas would continuously fill the entire volume within GMAs. We conclude that the GMAs are most likely not just confusion of multiple GMCs, but instead must be discrete structures. The GMCs coagulate and form GMAs in spiral arms. Such mass concentrations would be susceptible to kinematic fragmentation in high shear gradients across the spiral arms. In fact, the shear gradients are 200–600 km s^{-1} kpc^{-1} (Figure 1(b)), large enough to pull apart the GMAs against their self-gravity; the shear timescale, defined as the inverse of Oorts A-constant, is comparable to the free-fall timescale (~5–10 Myr). In addition, the GMAs in our images are in virtually all instances elongated along the spiral arms, instead of the round shapes expected if they are strongly self-gravitating. Formation of massive GMAs without an aid of gravity is seen in theoretical models due to GMC agglomeration in the spiral density wave (Dobbs & Bonnell 2006), and due to hydrodynamic instabilities triggered by strong shear upon entering the spiral arms (Wada & Koda 2004; Wada 2008).

The remnants of fragmented GMAs are seen in the interarm regions. Optical and infrared images show spur structures emerging from the spiral arms into the interarm regions (La Vigne et al. 2006) as dark filamentary lanes originating on the outside (downstream) of spiral arms (Figure 3). A few spurs have also been detected in CO line (Corder et al. 2008) and in Figure 3 here. They are formed by fragmentation of GMAs leaving the arms into the interarm regions. With the observed shear motions, GMAs would naturally shear into such filamentary spur structures. The total masses of spurs are a few $\times 10^{6-7}\, M_\odot$, approaching the masses of typical GMAs ($\sim 10^7\, M_\odot$).

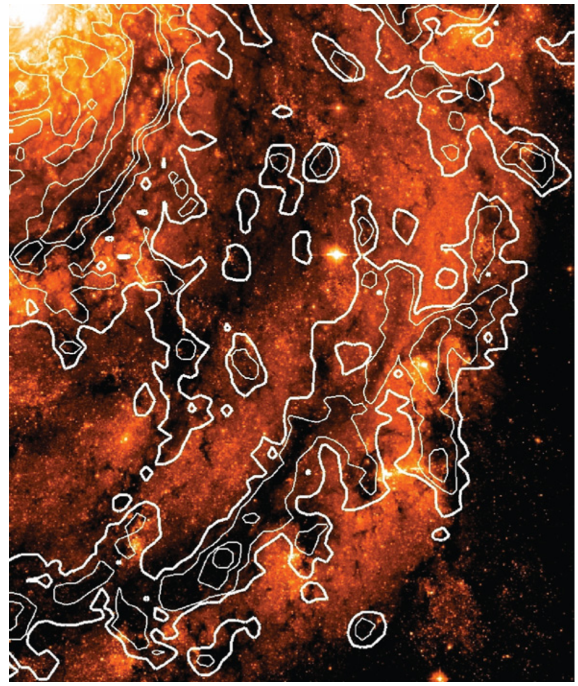


Figure 3. Spurs in interarm regions. Spurs that originate from the spiral arms and extend into the interarm regions are seen as optical extinction in the B-band image from *the Hubble Space Telescope* (*HST*) archive (color). Molecular gas (contours) traces the spurs, possibly the fragmented remnants of GMAs. Contours are at 3, 5, 9, and 13σ in each velocity channel, and the lowest contour is presented with a thick line. The spurs have very narrow line widths and are seen clearly in channel maps, but not as much in an integrated intensity map. We therefore overlaied the contours of all channels with emission exceeding 3σ.

These new observations suggest that the evolution of the dense ISM in M51 is dynamically driven. The GMCs coalesce into GMAs as they flow into the spiral arms and the cloud orbits converge in the spiral arm. The very massive GMA seen in the spiral arms must have lifetimes comparable to the time needed to cross the arms (~ 2–5×10^7 yr). On leaving the spiral arms, these GMAs are fragmented by the strong shear motions and then ejected into the downstream interarm regions as lower mass GMCs. Our new observations reveal over a hundred of the most massive GMCs ($> 4 \times 10^5\, M_\odot$) in the interarm regions. These GMCs are detected throughout the interarm areas and therefore must have lifetimes comparable with the interarm-crossing time of 10^8 yr. The majority of the interarm molecular gas is not resolved at our current detection limit $\sim 4 \times 10^5\, M_\odot$—thus, the fragmentation of GMAs must proceed to even lower mass GMCs. It is clear that most of the molecular gas is converted not simply to H I but to GMCs, since the molecules dominate the overall gas abundance in the major part of the disk (central ~12 kpc). The lifetimes of the lower mass GMCs require more sensitive observations.

We thank an anonymous referee for thoughtful comments. Support for CARMA construction was derived from the Gordon and Betty Moore Foundation, the Eileen and Kenneth Norris Foundation, the Caltech Associates, the states of California, Illinois, and Maryland, and the National Science Foundation. Ongoing CARMA development and operations are supported by the National Science Foundation under a cooperative agreement, and by the CARMA partner universities. This research is partially supported by HST-AR-11261.01.

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