Magnetic fields and spiral arms

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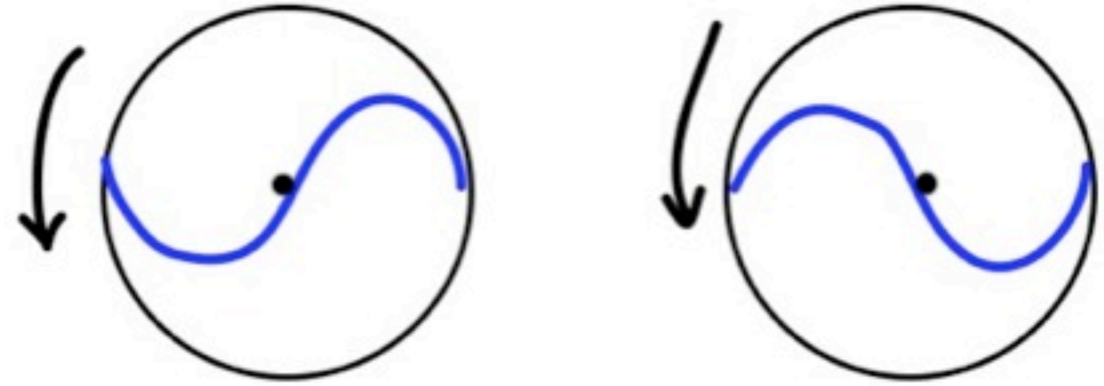
Outline

Theory and observations of:

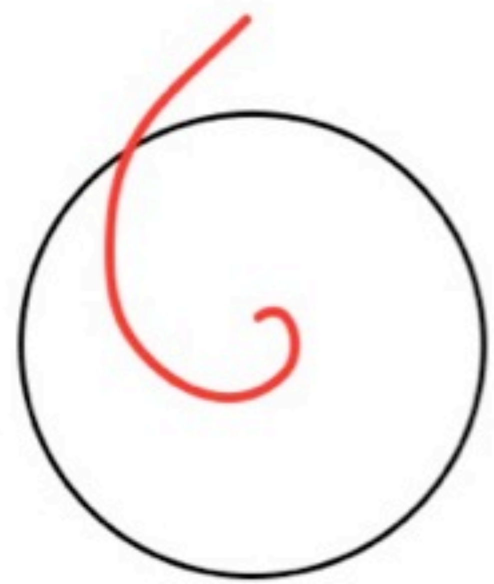
- Spiral arms
- Shocks
- Magnetic fields in spiral arms

Spiral arms: origins

- Density wave
- Bar driven
- Propagating fronts
- Transient arms
- Shape of arms



trailing leading

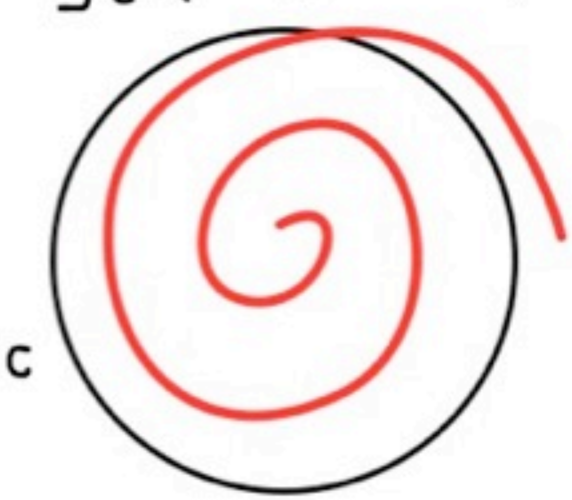


winding problem

$R = 10\,\mathrm{kpc}$

$t = 10\,\mathrm{Gyr}$

$\Omega R = 200\,\mathrm{km/s}$



$$\Delta R = \frac{2\pi R}{\omega t\, p} \approx 0.3\,\mathrm{kpc}$$

ON THE SPIRAL STRUCTURE OF DISK GALAXIES

C. C. LIN AND FRANK H. SHU
Department of Mathematics, Massachusetts Institute of Technology
Received March 20, 1964

ABSTRACT

It is shown that gravitational instability is a plausible basis for the formation of the spiral pattern in disk galaxies An explicit asymptotic formula is obtained for the form of the spiral. It gives reasonable numerical results for the galaxy, and qualitatively satisfactory trends for normal spirals of various types.

I. INTRODUCTION

The mechanism for the formation of the spiral patterns observed in most disk-shaped galaxies has not yet been fully understood. There is little doubt, from the observational data available, that these magnificent manifestations are associated with the interstellar gas and the brilliant young stars born in them. But could the old stars also play an important role in the formation of the spiral structure?

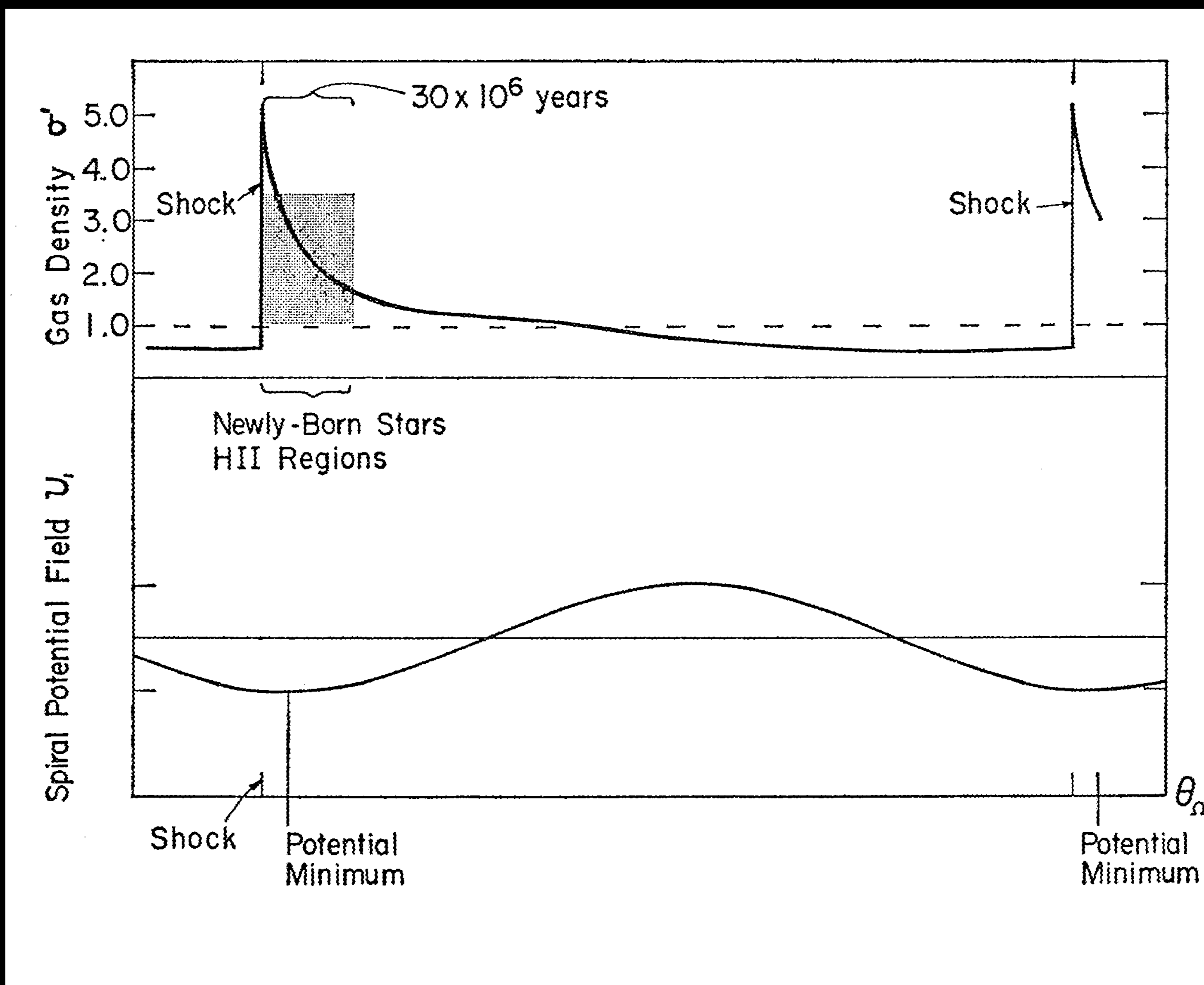
To construct a theory of the spiral structure, one must bear in mind the following important components of a galaxy:

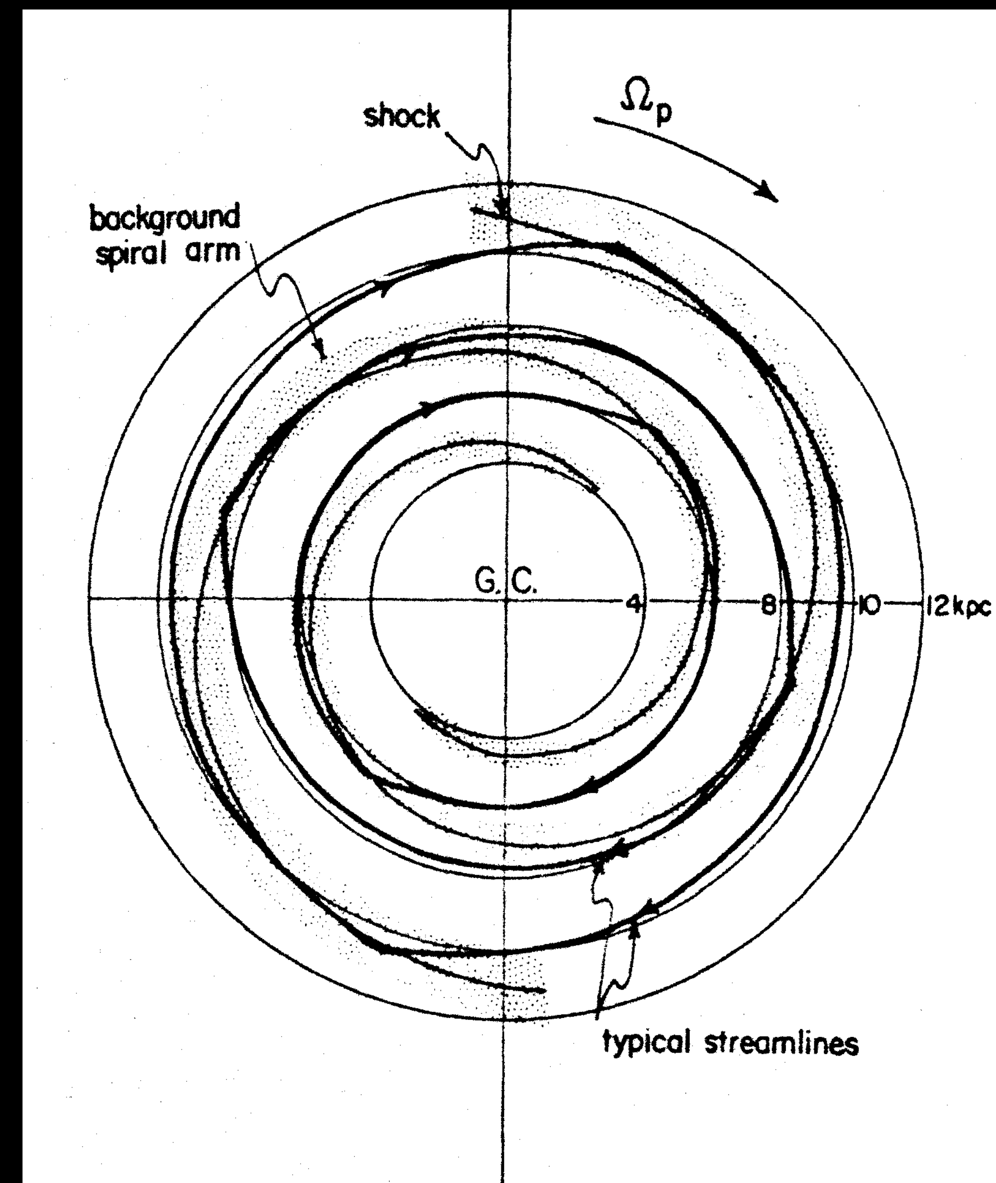
a) *The stars*—with their gravitational forces, circular velocity, and velocity dispersion
b) *The interstellar gas*—with *its* gravitational field and pressure
c) *The magnetic field*—which exerts its influence through the highly conducting interstellar gas.

A complete theory should take all these components and forces into account, and put their relative importance into perspective. Such a theory is not yet available.

LARGE-SCALE SHOCK FORMATION IN SPIRAL GALAXIES AND ITS IMPLICATIONS ON STAR FORMATION

W. W. Roberts*





APPLICATION OF THE DENSITY-WAVE THEORY TO THE SPIRAL STRUCTURE OF THE MILKY WAY SYSTEM. III. MAGNETIC FIELD: LARGE-SCALE HYDROMAGNETIC SHOCK FORMATION

WILLIAM W. ROBERTS, JR.

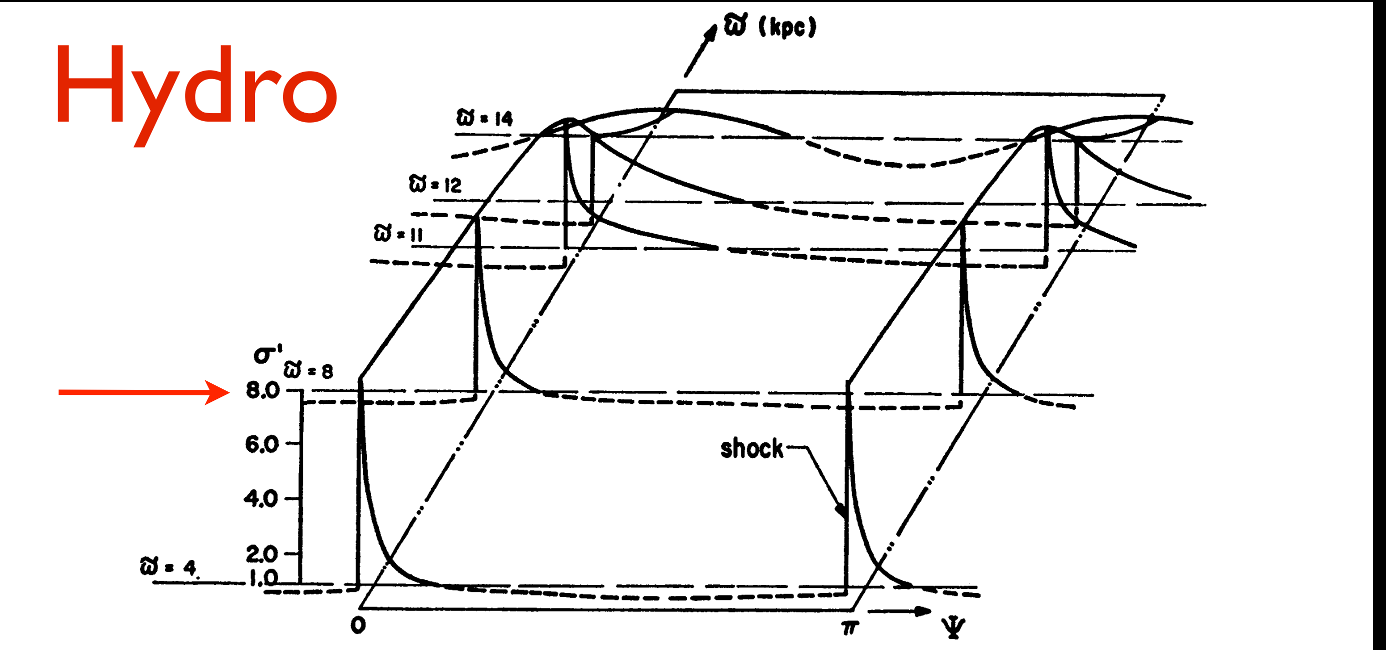
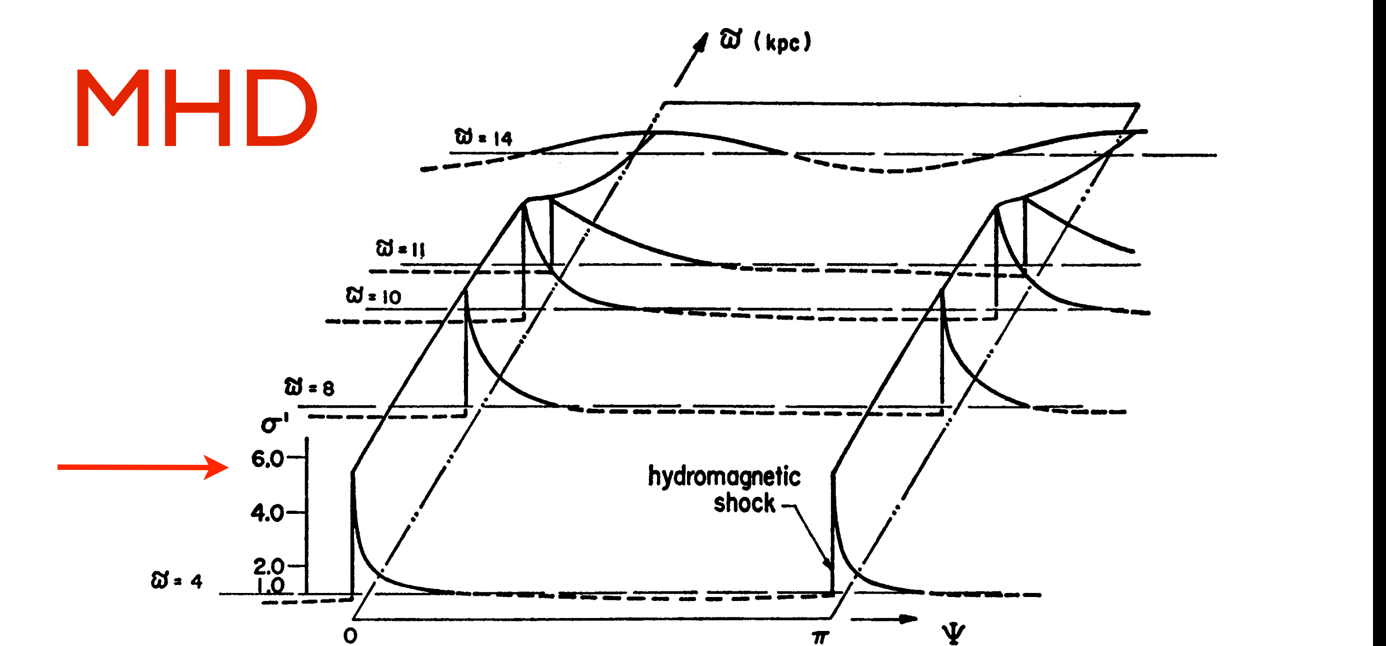


FIG. 1.—Gas density distribution in the TASS picture without magnetic field. The values taken on by the parameters are: $\langle H_0^2\rangle^{1/2} = 0$ microgauss corresponding to $a_m = 0$ km sec^{-1}, $a = 8$ km sec^{-1}, $F = 5$ percent, $\tan i = \frac{1}{7}$, $\Omega_p = 12.5$ km sec^{-1} kpc^{-1}, and ϖ is in the range from 3–4 kpc to 12–13 kpc.



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doi:10.1111/j.1365-2966.2009.16161.x

Simulations of the grand design galaxy M51: a case study for analysing tidally induced spiral structure

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ABSTRACT

We present hydrodynamical models of the grand design spiral M51 (NGC 5194), and its interaction with its companion NGC 5195. Despite the simplicity of our models, our simulations capture the present-day spiral structure of M51 remarkably well, and even reproduce details such as a kink along one spiral arm, and spiral arm bifurcations. We investigate the offset between the stellar and gaseous spiral arms, and find at most times (including the present day) there is no offset between the stars and gas within our error bars. We also compare our simulations with recent observational analysis of M51. We compute the pattern speed versus radius, and similar to observations, find no single global pattern speed. We also show that the spiral arms cannot be fitted well by logarithmic spirals. We interpret these findings as evidence that M51 does not exhibit a quasi-steady density wave, as would be predicted by density wave theory. The internal structure of M51 derives from the complicated and dynamical interaction with its companion, resulting in spiral arms showing considerable structure in the form of short-lived kinks and bifurcations. Rather than trying to model such galaxies in terms of global spiral modes with fixed pattern speeds, it is more realistic to start from a picture in which the spiral arms, while not being simple material arms, are the result of tidally induced kinematic density 'waves' or density patterns, which wind up slowly over time.

The Astrophysical Journal, 735:101 (11pp), 2011 July 10 doi:10.1088/0004-637X/735

OBSERVATIONAL EVIDENCE AGAINST LONG-LIVED SPIRAL ARMS IN GALAXIES

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ABSTRACT

We test whether the spiral patterns apparent in many large disk galaxies should be thought of as dynamical features that are stationary in a corotating frame for $\gtrsim t_{\rm dyn}$, as implied by the density wave approach for explaining spiral arms. If such spiral arms have enhanced star formation (SF), observational tracers for different stages of the SF sequence should show a spatial ordering, from upstream to downstream in the corotating frame: dense H I, CO, tracing molecular hydrogen gas, 24 μm emission tracing enshrouded SF, and UV emission tracing unobscured young stars. We argue that such a spatial ordering should be reflected in the angular cross-correlation (CC, in polar coordinates) using all azimuthal positions among pairs of these tracers; the peak of the CC should be offset from zero, in different directions inside and outside the corotation radius. Recent spiral SF simulations by Dobbs & Pringle show explicitly that for the case of a stationary spiral arm potential such angular offsets between gas and young stars of differing ages should be observable as cross-correlation offsets. We calculate the angular cross-correlations for different observational SF sequence tracers in 12 nearby spiral galaxies, drawing on a data set with high-quality maps of the neutral gas (H I, THINGS) and molecular gas (CO, HERACLES), along with 24 μm emission (*Spitzer*, SINGS); we include FUV images (*GALEX*) and 3.6 μm emission (*Spitzer*, IRAC) for some galaxies, tracing aging stars and longer timescales. In none of the resulting tracer cross-correlations for this sample do we find systematic angular offsets, which would be expected for a stationary dynamical spiral pattern of well-defined pattern speed. This result indicates that spiral density waves in their simplest form are not an important aspect of explaining spirals in large disk galaxies.

THE ASTROPHYSICAL JOURNAL, 763:94 (11pp), 2013 February 1 doi:10.1088/0004-637X/7

GEOMETRIC OFFSETS ACROSS SPIRAL ARMS IN M51: NATURE OF GAS AND STAR FORMATION TRACERS

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ABSTRACT

We report measurements of geometric offsets between gas spiral arms and associated star-forming regions in the grand-design spiral galaxy M51. These offsets are a suggested measure of the star formation timescale after the compression of gas at spiral arm entry. A surprising discrepancy, by an order of magnitude, has been reported in recent offset measurements in nearby spiral galaxies. Measurements using CO and Hα emission find large and ordered offsets in M51. On the contrary, small or non-ordered offsets have been found using the H I 21 cm and 24 μm emissions, possible evidence against gas flow through spiral arms, and thus against the conventional density-wave theory with a stationary spiral pattern. The goal of this paper is to understand the cause of this discrepancy. We investigate potential causes by repeating those previous measurements using equivalent data, methods, and parameters. We find offsets consistent with the previous measurements and conclude that the difference of gas tracers, i.e., H I versus CO, is the primary cause. The H I emission is contaminated significantly by the gas photodissociated by recently formed stars and does not necessarily trace the compressed gas, the precursor of star formation. The H I gas and star-forming regions coincide spatially and tend to show small offsets. We find mostly positive offsets with substantial scatter between CO and Hα, suggesting that gas flow through spiral arms (i.e., density wave) though the spiral pattern may not necessarily be stationary.

Spiral structure in nearby galaxies – I. Sample, data analysis and overview of results

S. Kendall,* R. C. Kennicutt and C. Clarke

modes. There is no evidence that bars preferentially trigger the spirals, but they do appear to stir up non-axisymmetric structure in the disc. In contrast, there is evidence that strong/close tidal interactions with companion galaxies are associated with strong two-armed spiral structure in the IR, though there are a number of galaxies with relatively weak IR spiral structure that do not possess such companions.

The Astronomical Journal, 137:4487–4516, 2009 May
doi:10.1088/0004-6256/137/5/448

DO BARS DRIVE SPIRAL DENSITY WAVES?

maybe

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We present deep near-infrared
of a selected sample of near
sample covers a range of Hub
the spirals correlate with thos
has been predicted by theoret
at high redshift. Analysis of
where effects of extinction a
few excessively strong bars.
is relatively weak. We find t
the presence of a very strong
pattern speed, but that this m

The Astrophysical Journal Letters, 715:L56–L61, 2010 May 20
doi:10.1088/2041-8205/71

BARS DO DRIVE SPIRAL DENSITY WAVES

yes, in a statistical sense

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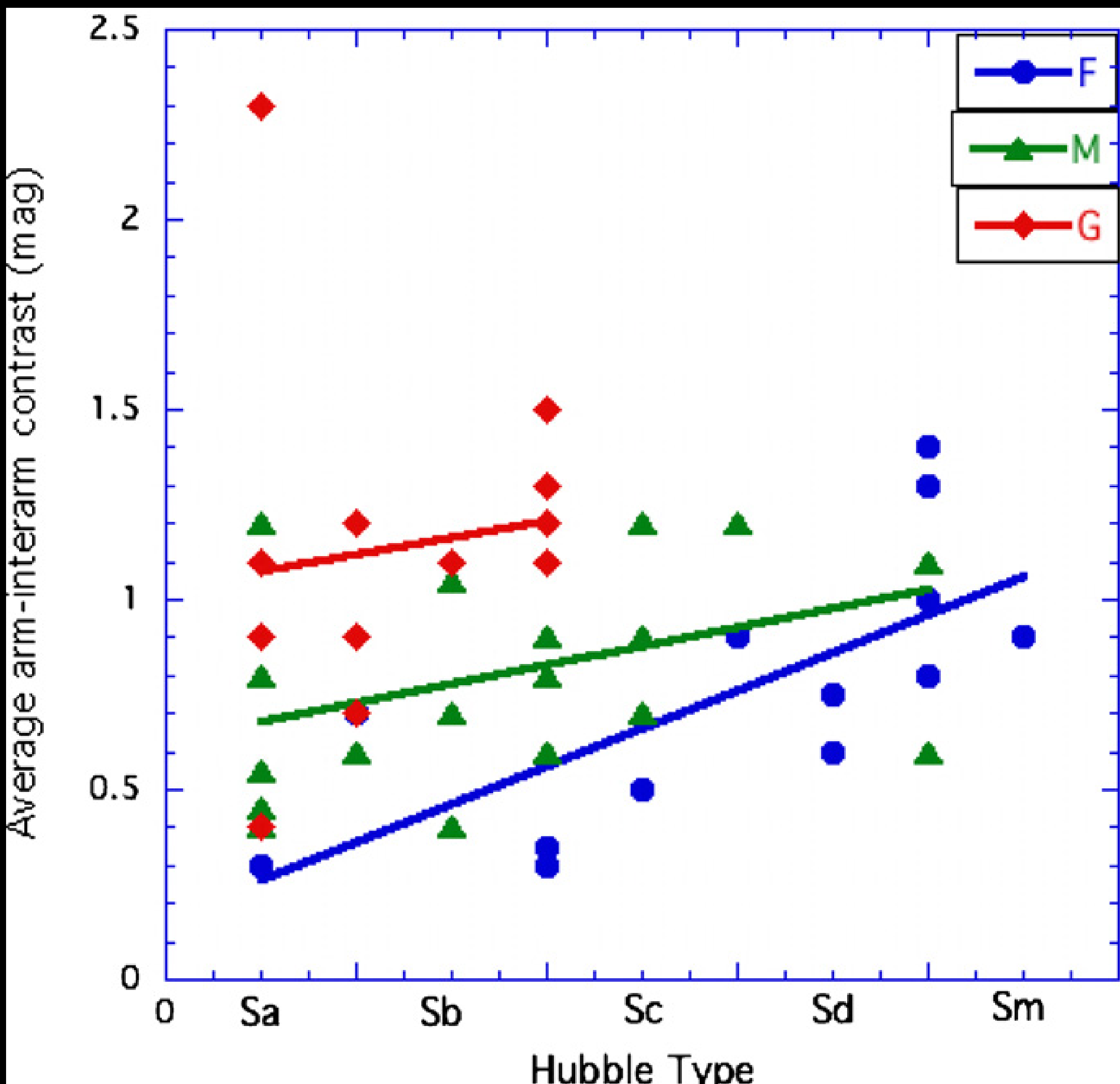
ABSTRACT

Recently, Buta et al. examined the question "Do Bars Drive Spiral Density Waves?", an idea supported by theoretical studies and also from a preliminary observational analysis. They estimated maximum bar strengths Q_b, maximum spiral strengths Q_s, and maximum $m = 2$ arm contrasts A_{2s} for 23 galaxies with deep Anglo-Australian Telescope (AAT) K_s-band images. These were combined with previously published Q_b and Q_s values for 147 galaxies from the Ohio State University Bright Spiral Galaxy Survey (OSUBSGS) sample and with the 12 galaxies from Block et al. Weak correlation between Q_b and Q_s was confirmed for the combined sample, whereas the AAT subset alone showed no significant correlations between Q_b and Q_s, nor between Q_b and A_{2s}. A similar negative result was obtained in Durbala et al. for 46 galaxies. Based on these studies, the answer to the above question remains uncertain. Here we use a novel approach, and show that although the correlation between the *maximum* bar and spiral parameters is weak, these parameters do correlate when compared *locally*. For the OSUBSGS sample, a statistically significant correlation is found between the local spiral amplitude, and the forcing due to the bar's potential at the same distance, out to ≈1.6 bar radii (the typical bar perturbation is then of the order of a few percent). Also for the sample of 23 AAT galaxies of Buta et al., we find a significant correlation between local parameters out to ≈1.4 bar radii. Our new results confirm that, at least in a statistical sense, bars do indeed drive spiral density waves.

GRAND DESIGN AND FLOCCULENT SPIRALS IN THE *SPITZER* SURVEY OF STELLAR STRUCTURE IN GALAXIES (S^4G)

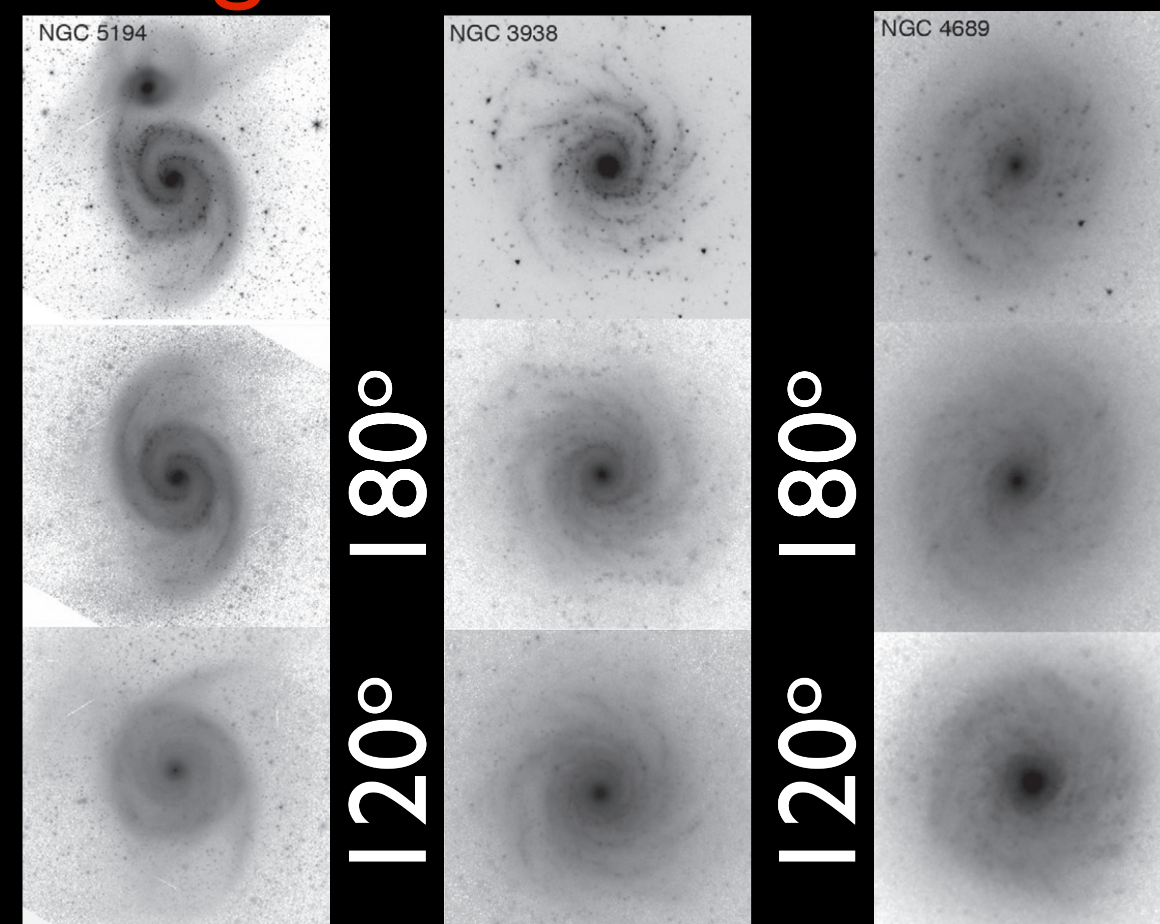
DEBRA MELOY ELMEGREEN[1], BRUCE G. ELMEGREEN[2], ANDREW YAU[1], E. ATHANASSOULA[3], ALBERT BOSMA[3], RONALD J. BUTA[4],



grand design

multiple arm

flocculent



$$A(r) = 2.5 \log \left[\frac{2 I_{\mathrm{arm}}(r)}{I_{\mathrm{interarm1}}(r) + I_{\mathrm{interarm2}}(r)} \right]$$

Spiral arms: origins

- Density wave
- Bar driven
- Propagating fronts
- Transient arms: interaction, ...

Shocks

- Compression of gas
- Compression of magnetic field
- Decompression!

upstream | downstream

$$v_u \rho_u = v_d \rho_d$$

<u>not radiating</u> (adiabatic)

$$\frac{\rho_u}{\rho_d} = \frac{\gamma-1}{\gamma+1} + \frac{2}{\gamma+1}\frac{1}{Ma^2},$$

$$\approx \frac{\gamma-1}{\gamma+1} = \frac{1}{4}, \quad Ma \gg 1, \quad \gamma = 5/3$$

<u>radiating</u> (isothermal)

$$\frac{\rho_u}{\rho_d} = \frac{c_s^2}{v_u^2} = \frac{1}{Ma^2}$$

upstream | downstream

$$\frac{B_{\parallel,u}}{\rho_u} = \frac{B_{\parallel,d}}{\rho_d}$$

$$B_{\perp,u} = B_{\perp,d}$$

adiabatic

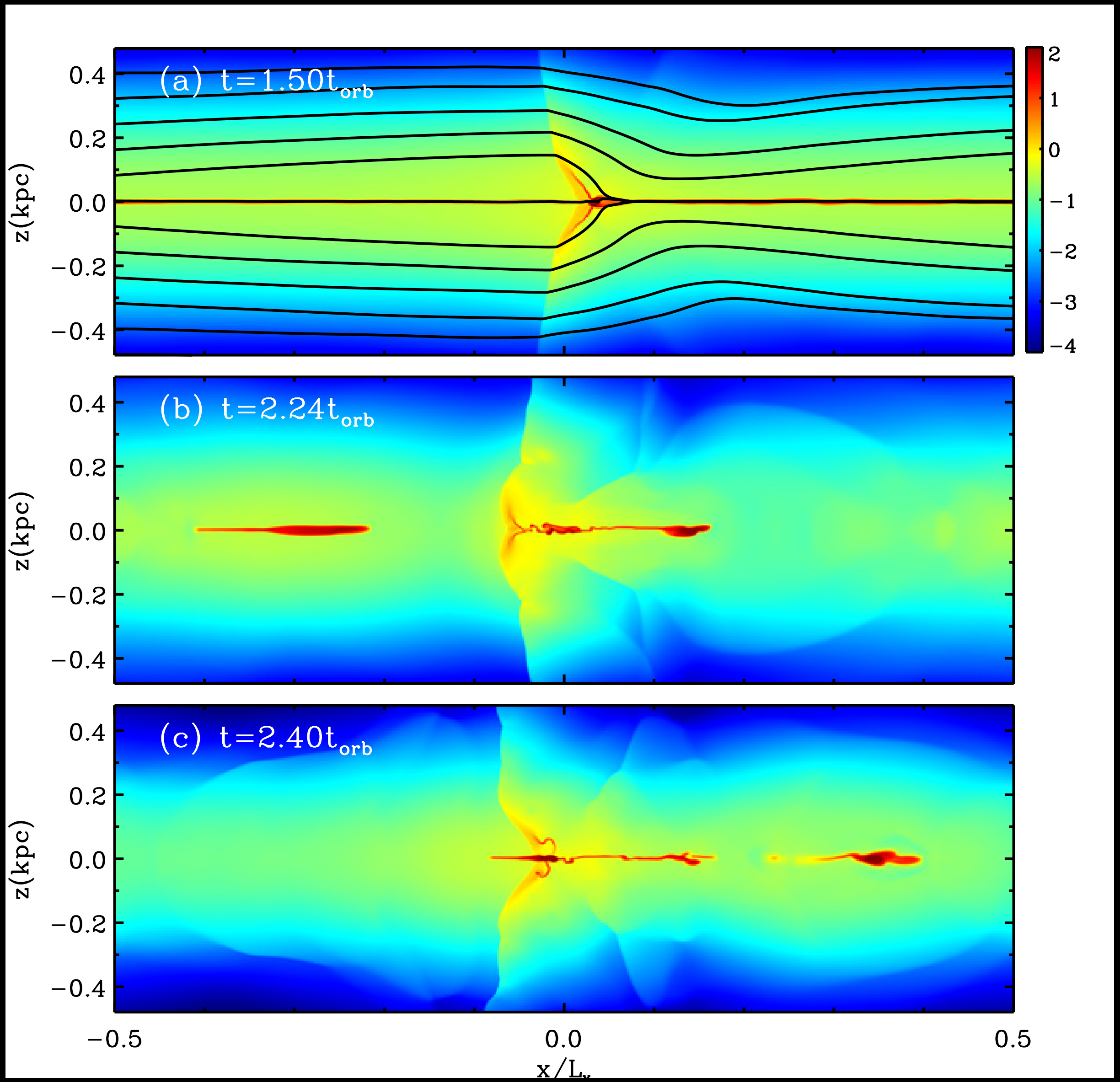
B has little effect on shock

isothermal

$$\frac{\rho_u}{\rho_d} = \frac{1}{\sqrt{2}}\frac{V_A}{V_u}, \quad V_A = B/2\sqrt{\pi\rho}$$

GALACTIC SPIRAL SHOCKS WITH THERMAL INSTABILITY IN VERTICALLY STRATIFIED GALACTIC DISKS

CHANG-GOO KIM[1], WOONG-TAE KIM[1], AND EVE C. OSTRIKER[2]



	distance	time
arm	10%	15%
expansion	20%	30%
interarm	70%	55%

Magnetic fields: observation

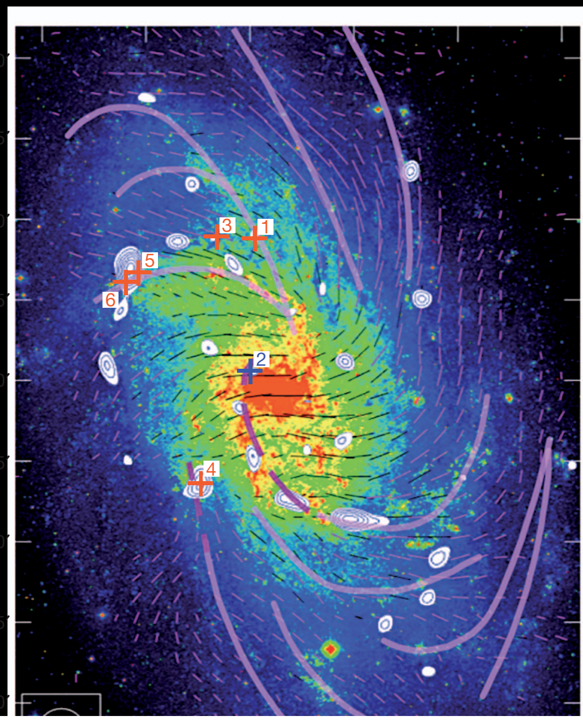
- Arm interarm contrasts in B and b
- Pitch angles and their variation
- B and formation of dense clouds

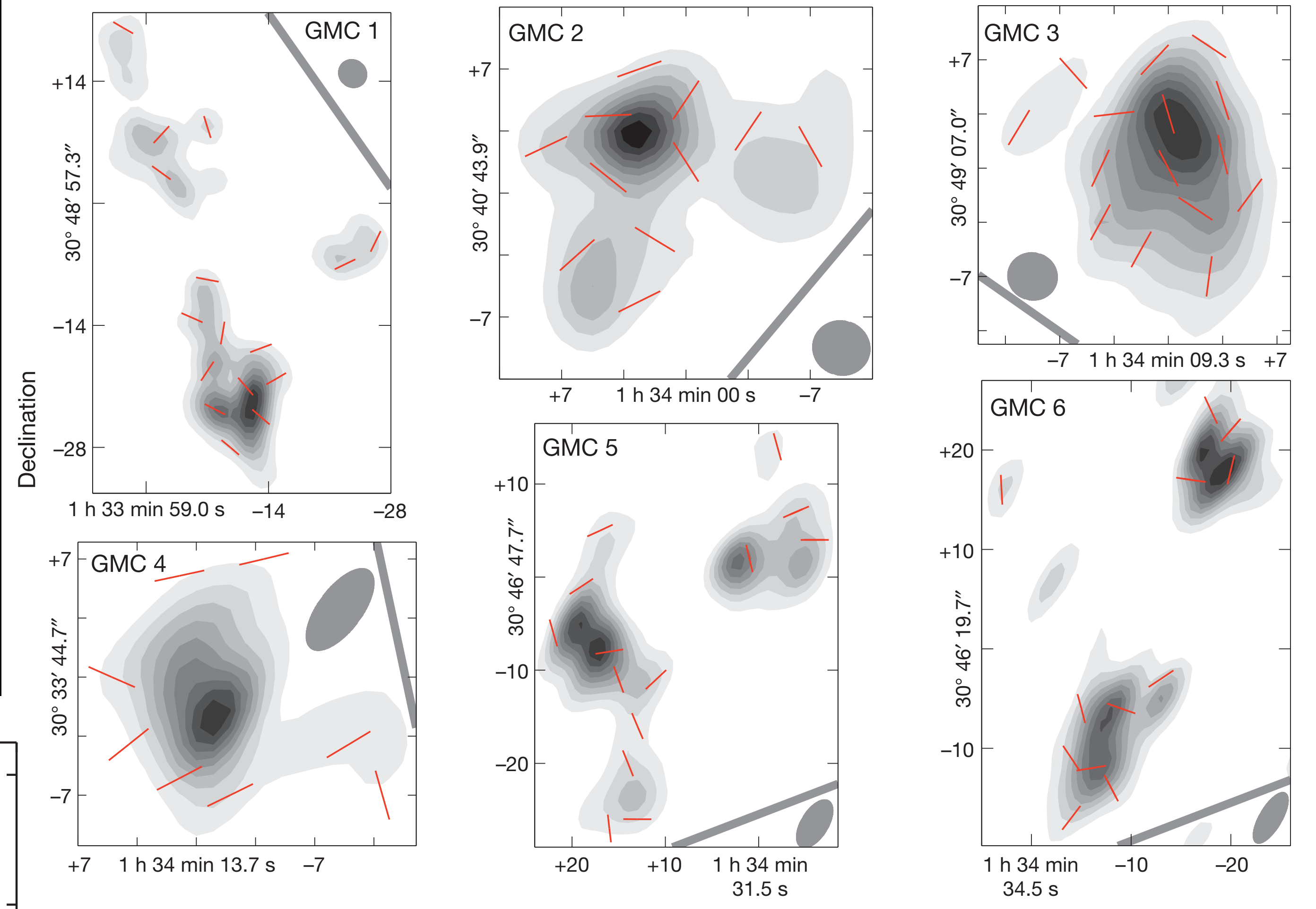
Pitch angles: B & spiral arms

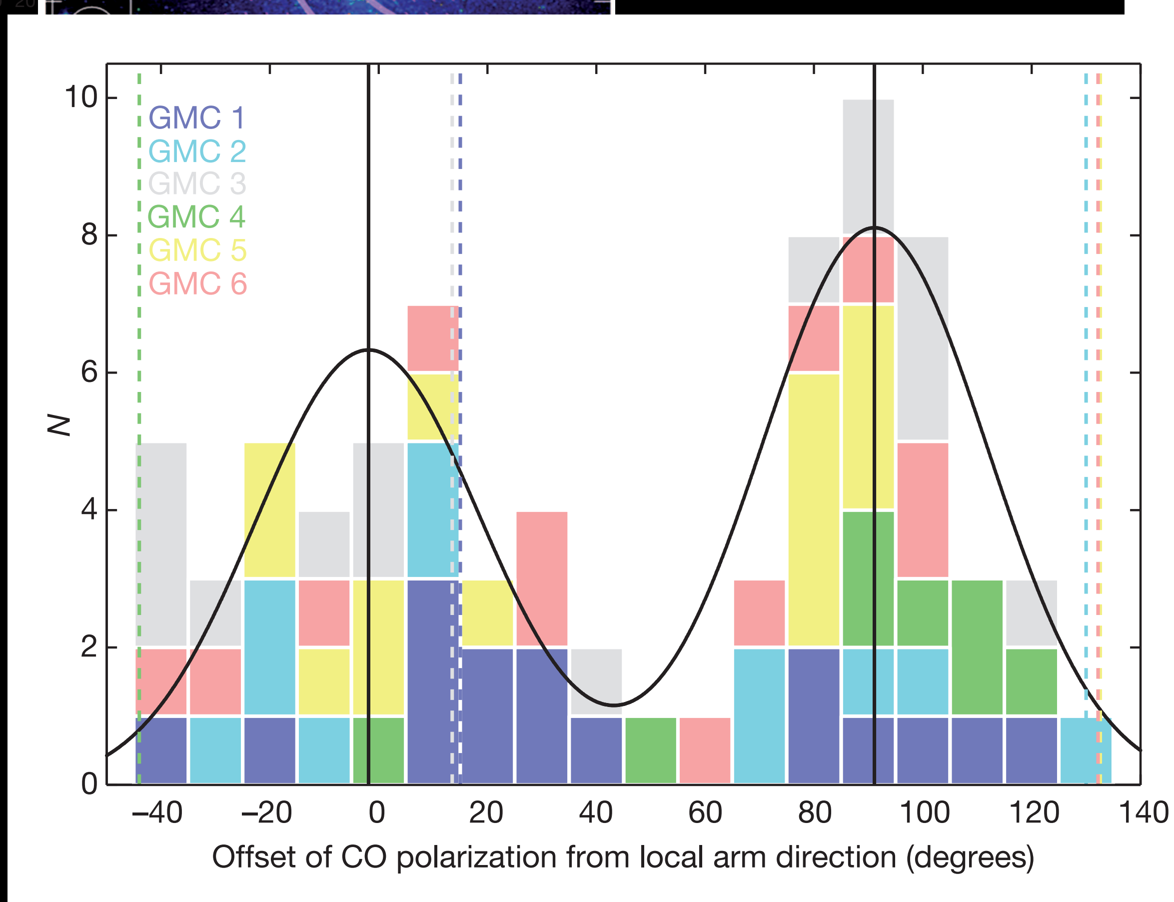
	pitch angle			
Galaxy	inner	outer	optical	B-field Ref.
IC 342	-20°±2	-16°±2	-19°±5	Krause et al. 1989
M31	-17°±4	-8°±3	-7°	Fletcher et al. 2004
M33	-48°±12	-42°±5	-26°±5	Tabatabaei et al. 2009
M51	-20°±1	-18°±1	-20°	Fletcher et al. 2011
M81	-14°±7	-22°±5	-11° → -14°	Krause et al. 1989
NGC 6946	-27°±2	-21°±2		Ehle & Beck 1993

The alignment of molecular cloud magnetic fields with the spiral arms in M33

Hua-bai Li[1] & Thomas Henning[1]







Pitch angles: azimuth

Galaxy	amplitude of pitch angle variation	Ref.
IC 342	30°	Graeve & Beck 1988
M31	0°	Fletcher et al. 2004
M33	30°	Tabatabaei et al. 2008
M51	30°	Patrikeev, Fletcher et al. 2006
M81	50°	Beck et al. 1985
NGC 1566	0°	Ehle et al. 1996
NGC 6946	5°-9°	Ehle & Beck 1993

Case study: M51

Locate the arms!

Is B aligned at spiral shocks?

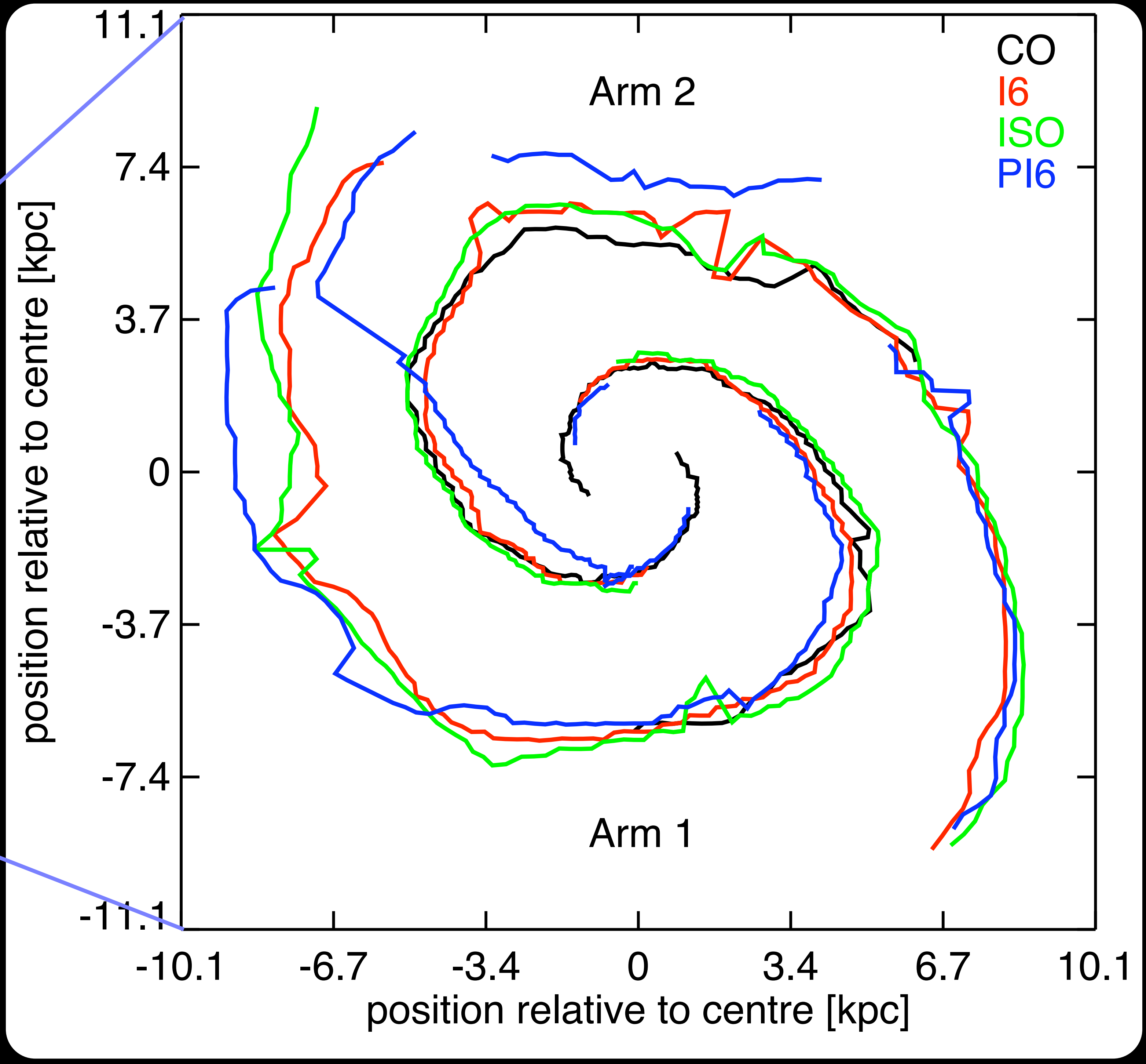
Is this due to compression or shear?

What is gas and B arm/interarm increase?

Is this compatible with theoretical expectation?

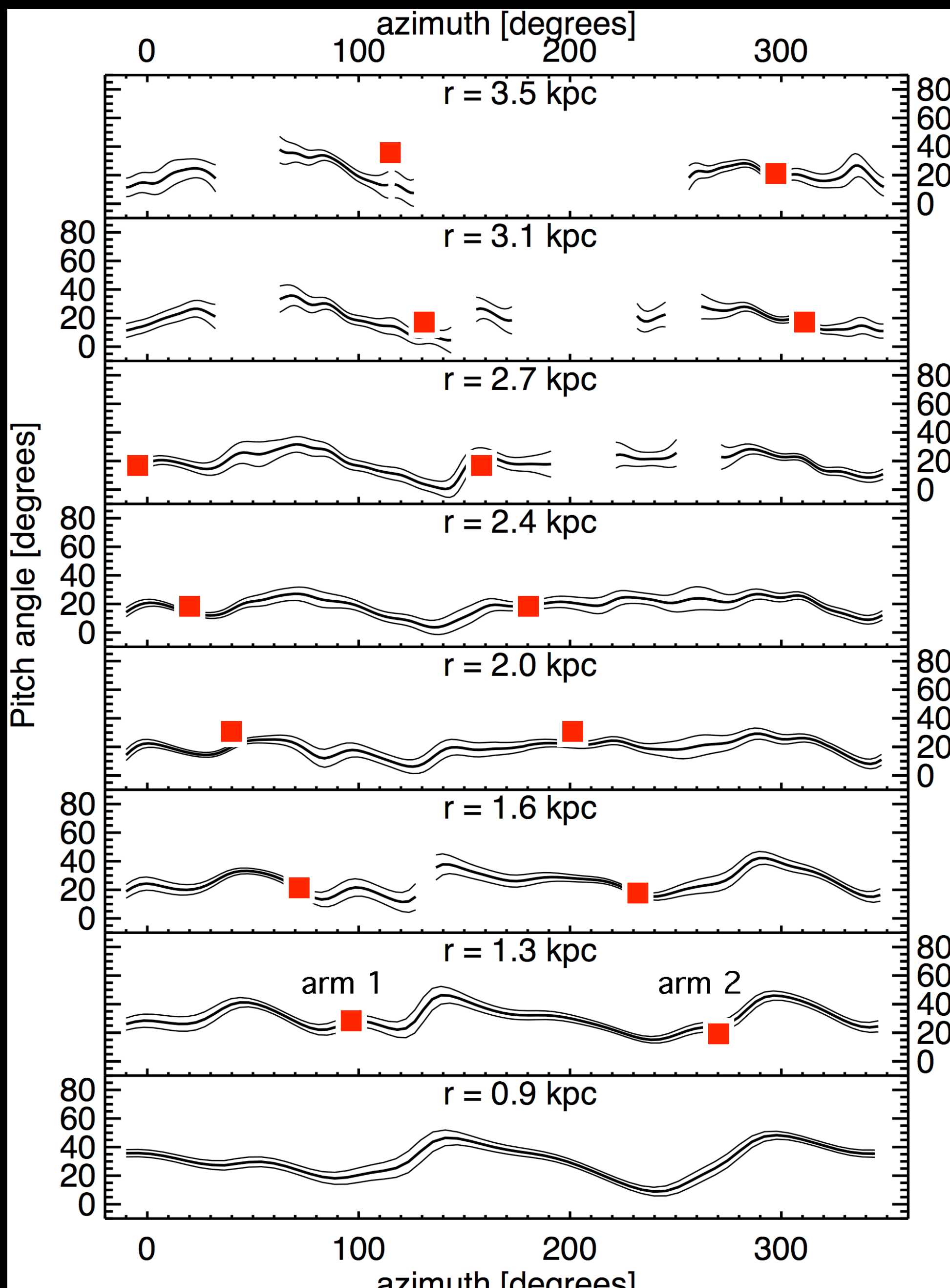
Patrikeev et al. 2006, Fletcher et al. 2011

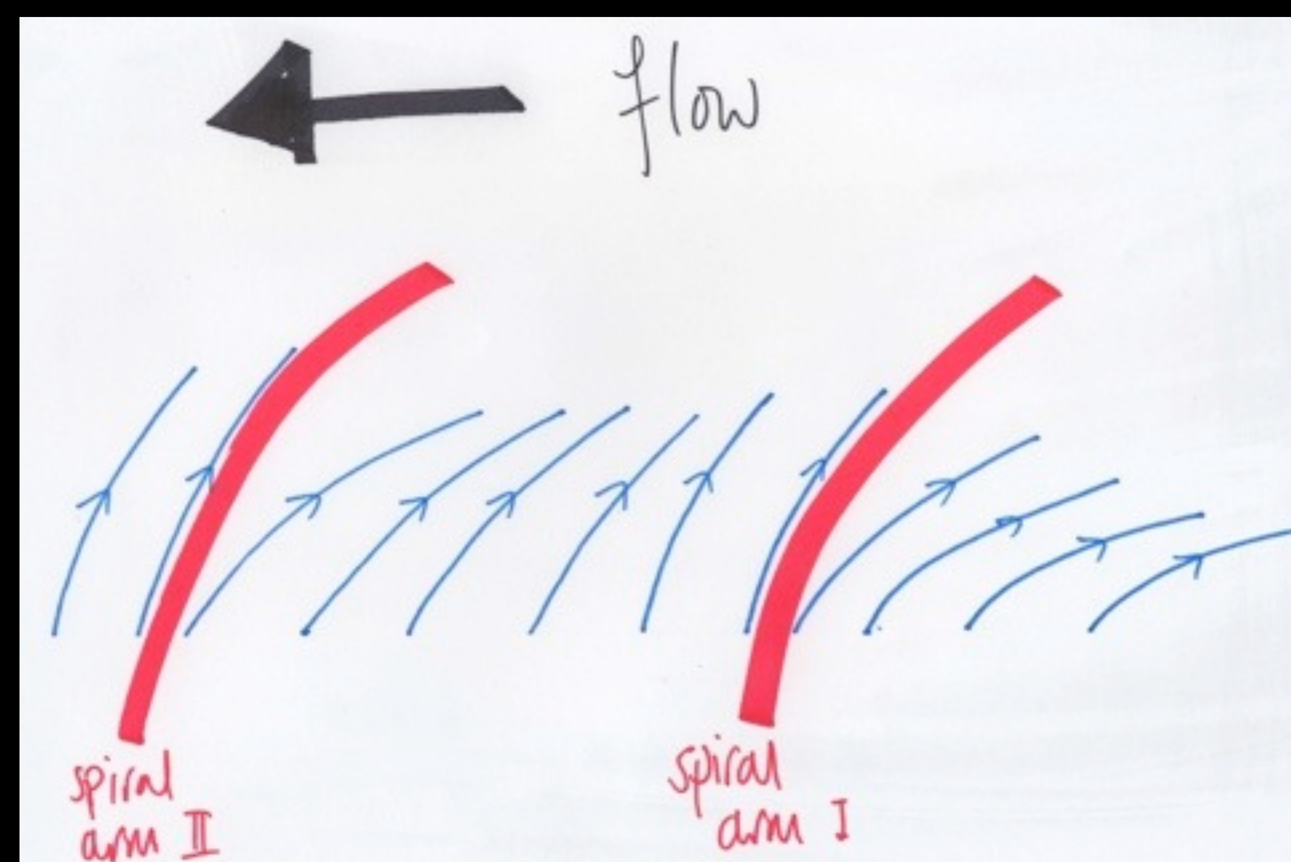
M51: position of arm ridges



Patrikeev et al. 2006

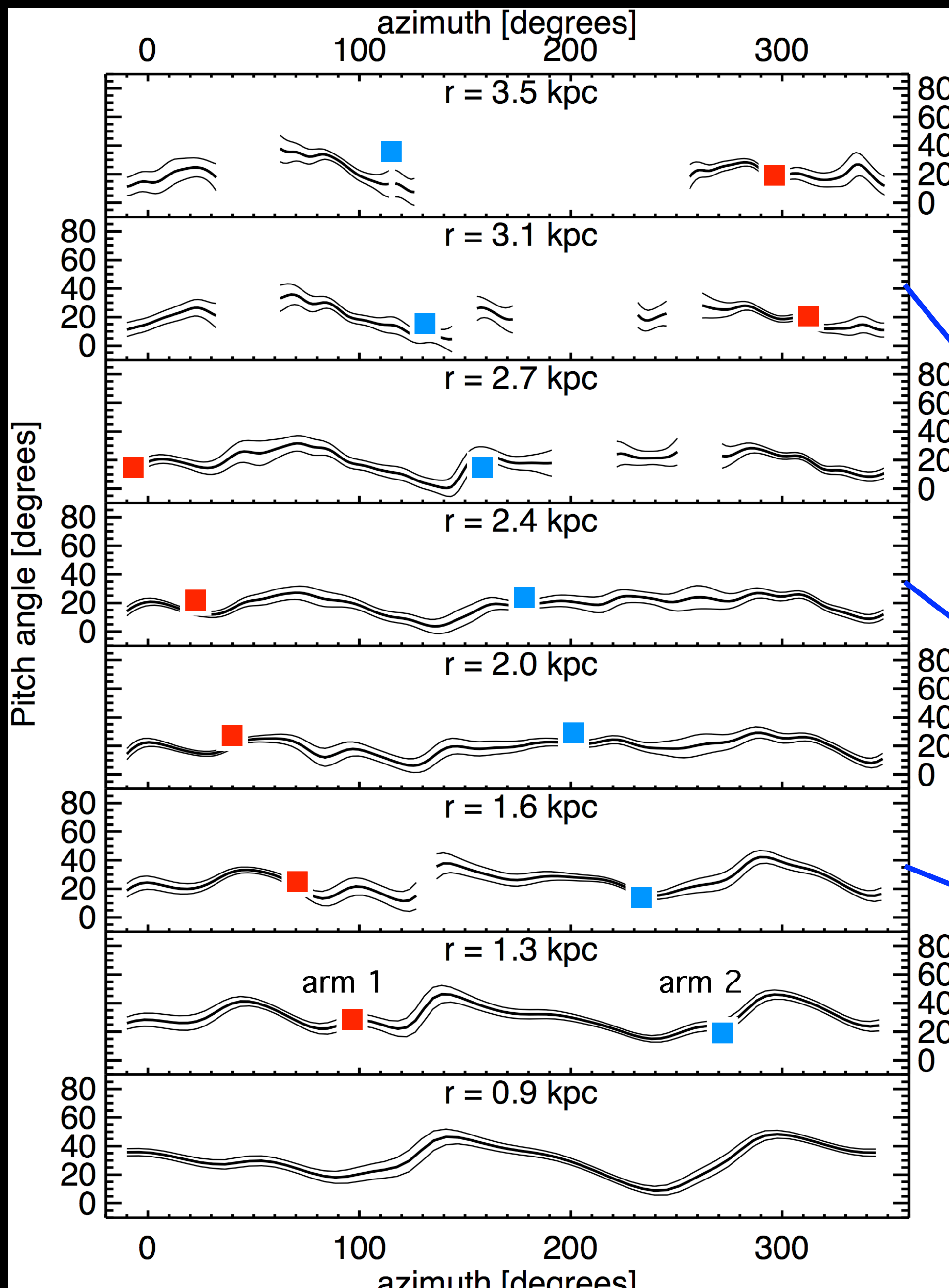
B aligned with arm at arm





Patrikeev, Fletcher et al. 2006

B and velocity field



v_r v_ϑ

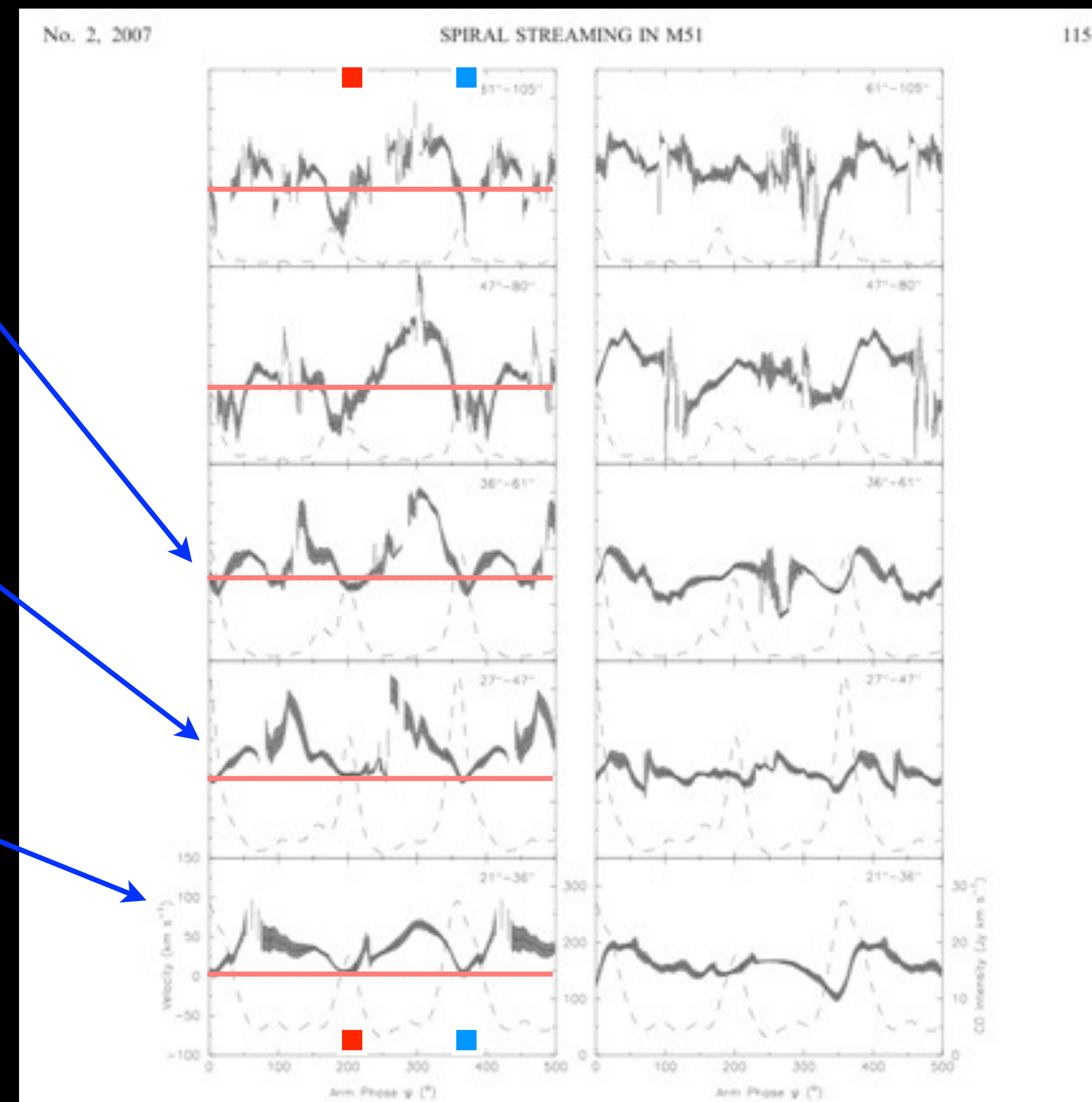


FIG. 14.—CO v_R (left panels) and v_θ (right panels) fits as a function of arm phase ψ in different annuli (with radii labeled in the upper right of each panel). The thickness of the line shows a range of $\pm 3\sigma$. Only v_R and v_θ fits with $3\sigma \leq 20$ km s^{-1} and ≤ 60 km s^{-1}, respectively, are shown. Dashed lines are the corresponding mean CO intensities, with the scale shown on the right ordinate. We assume a position angle of 170°, an inclination of 24°, and the center position and systematic velocity listed in Table 1. Fig. 16 shows the annular regions of M51 considered for these fits.

Patrikeev, Fletcher, et al. 2006

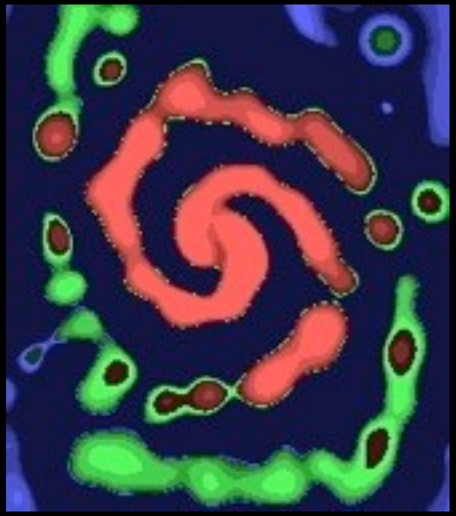
Shetty, Vogel et al. 2007

M51: Arm/interarm contrast

Emission	Average	Peak
HI + H2 column	4.5	5.0
Total radio 6cm	2.2	5.0
Polarized 6cm	1.0	≥7

Average: "mask" identifying gas arms

Peak: maximum contrast inner galaxy



Expected $I_{\rm syn}$ contrast

$$n_\gamma \mathrm{d}\gamma = K_\gamma \gamma^{-s} \mathrm{d}\gamma, \;\; s \simeq 3$$

$$\Delta\epsilon(\nu) \sim K_\gamma B^{(s+1)/2} \sim \rho^{(s-1)/2} \rho^{(s+1)/2} \sim \rho^s$$

cr energy increase

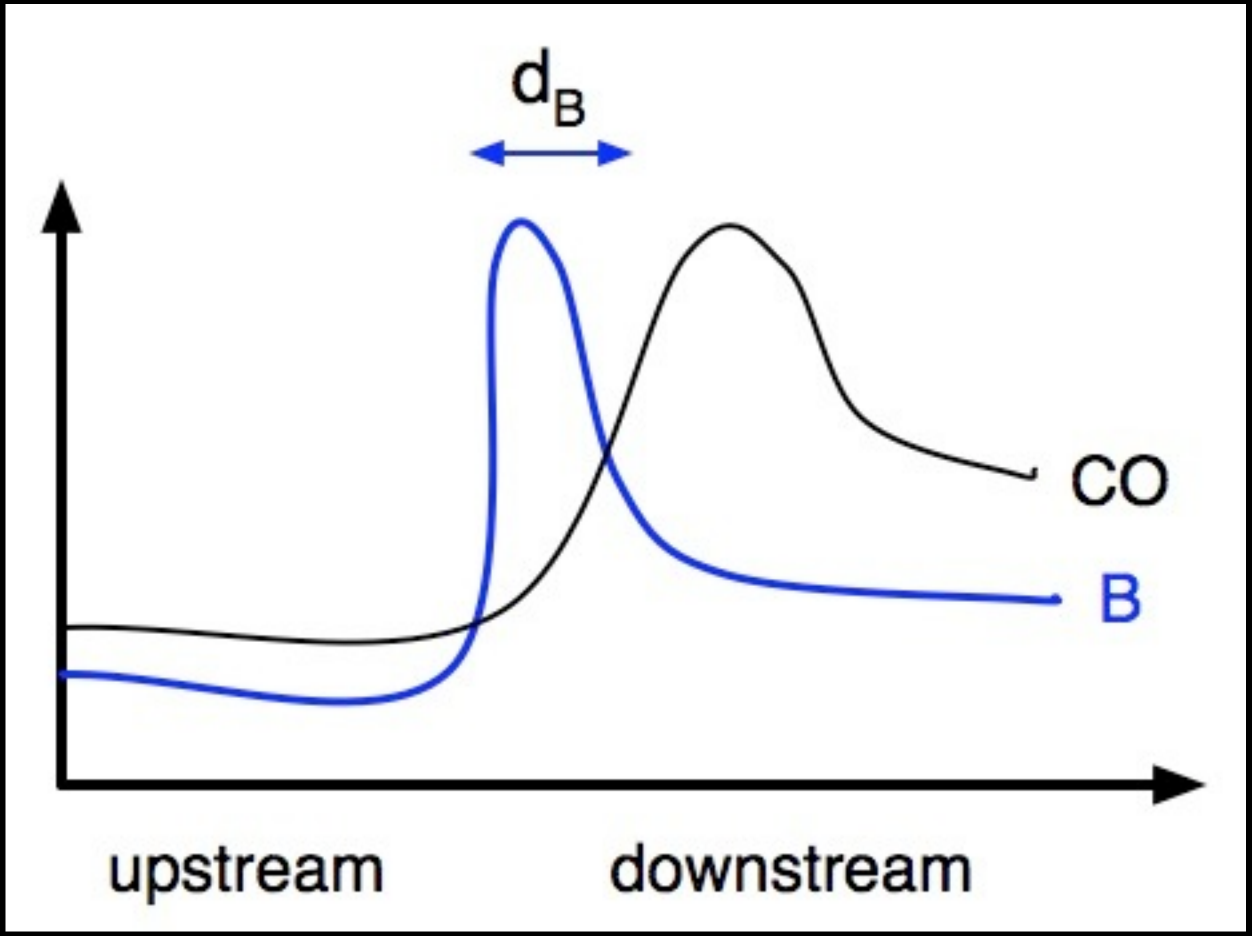
increased B
lower energy cr

$\Delta\epsilon \simeq 50$

Observed contrast: 2 to 5

Similar problem for polarization

M51: arm/interarm contrast explanation

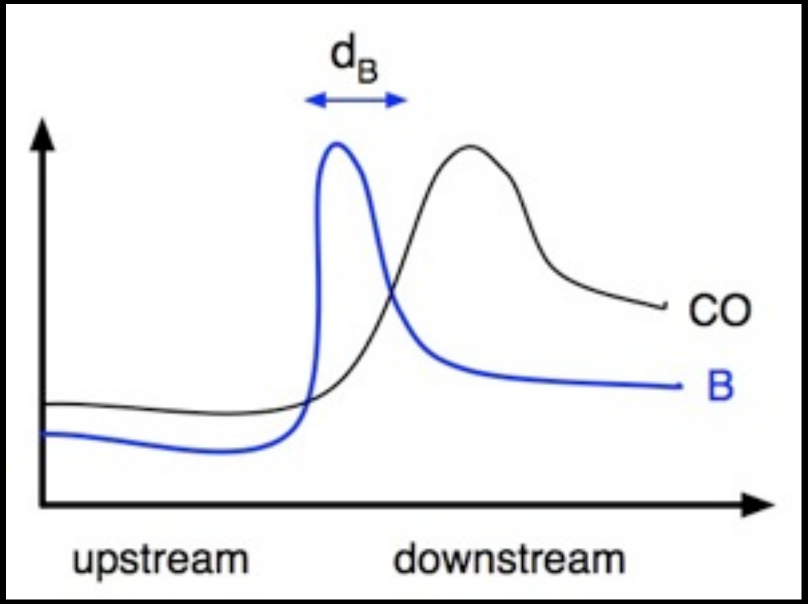


Resolution: narrow B-shock smaller than beam

Decoupling: ambient B detaches from dense clouds

Rarefaction: B decompresses downstream of shock

Resolution lowers contrast

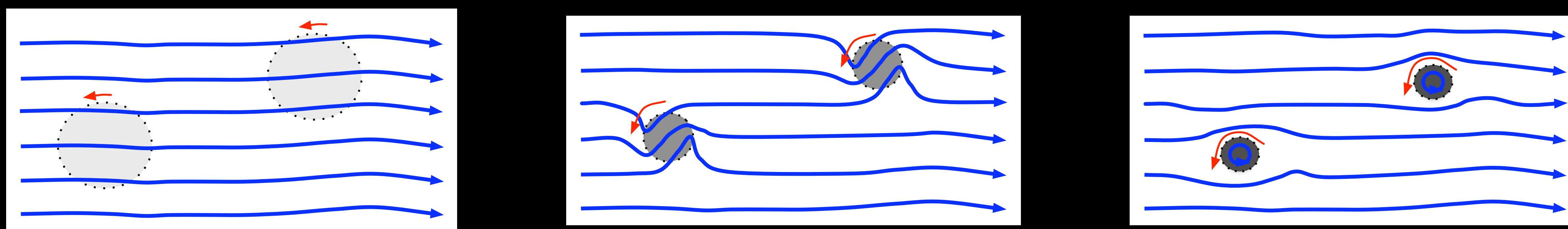


Shock width estimate:

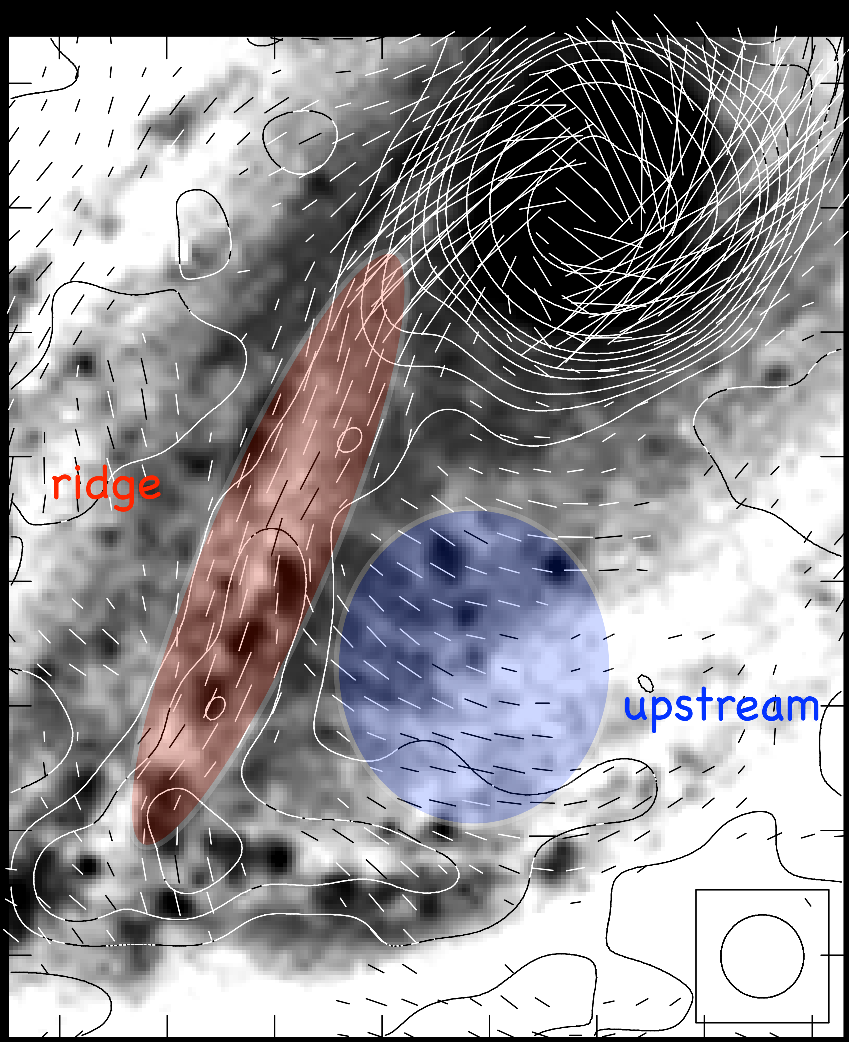
$$\Delta\epsilon_{\rm obs} \sim \Delta\epsilon_{\rm exp}\frac{d_B}{W} = 50\frac{d_B\,[\rm pc]}{150\,[\rm pc]} = 5$$

$$d_B \sim 15\,\rm pc$$

Decoupling: B from dense gas



Fletcher, Korpi, Shukurov 2008



Beck, Fletcher, Shukurov 2005

Barred galaxy
NGC 1097

THE ASTROPHYSICAL JOURNAL, 662: L75–L77, 2007 June 20

FORMATION OF OB ASSOCIATIONS IN GALAXIES

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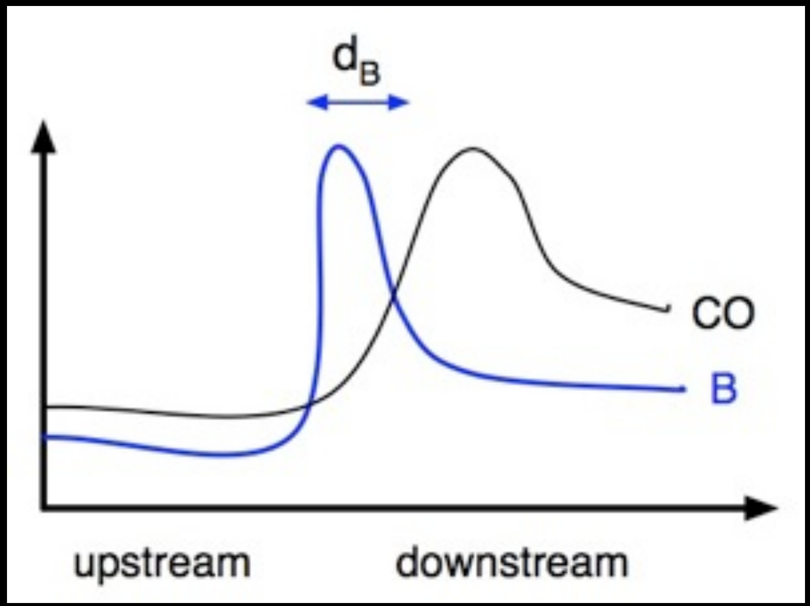
redistributed. Thus, gas that becomes supercritical and collapses can only do so by making the remaining gas more subcritical and less prone to collapse.

Rarefaction downstream

Initially isotropic small-scale magnetic field



$$\Delta\rho = 4$$

Compression: $\Delta b_\perp^2 \simeq 8$

Expansion: $\Delta b_\perp^2 \simeq 2$

Observed contrast in polarization: 1 to >7

Open questions

- What is the connection between spiral arms (stellar, gas) and spiral magnetic fields?
- Are magnetic fields important for astrophysics in spiral arms? (Shocks, residence time of gas, shape, ...)