RUHR-UNIVERSITÄT BOCHUM

RAPP Center

RUB

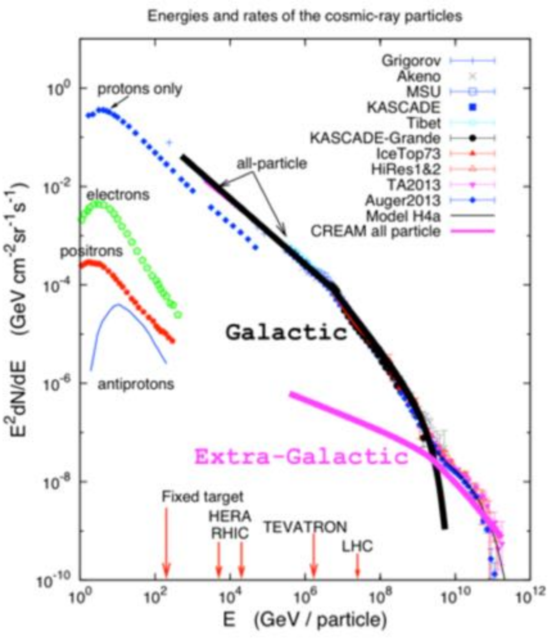
Observational evidence of CR driven galactic winds:? CRE propagation and magnetic fields in galactic halos

Ralf-Jürgen Dettmar, Ruhr-University Bochum

with V. Heesen, B. Adebahr, R. Beck, M. Krause,Y. Stein, M. Wezgowiec, A. Miskolczi, George Heald and the LOFAR MKSP & CHANGES teams

RUHR-UNIVERSITÄT BOCHUM

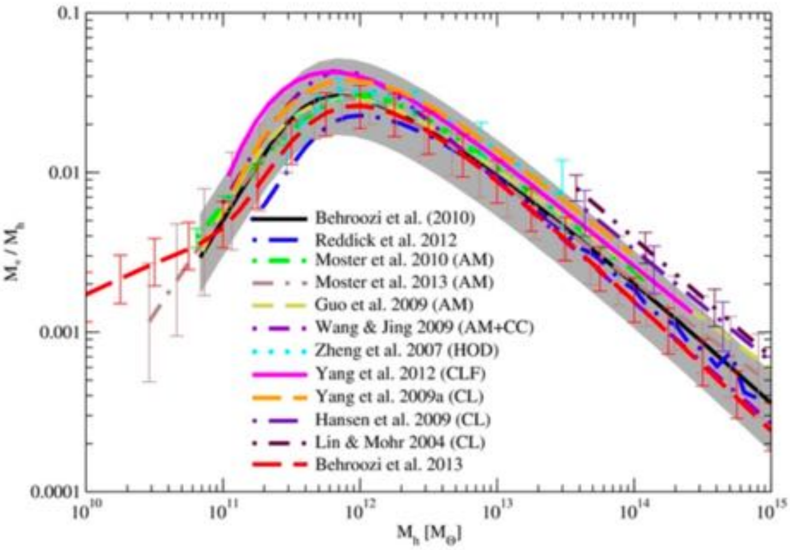
RUB



„IceCube Masterclass“

RUHR-UNIVERSITÄT BOCHUM

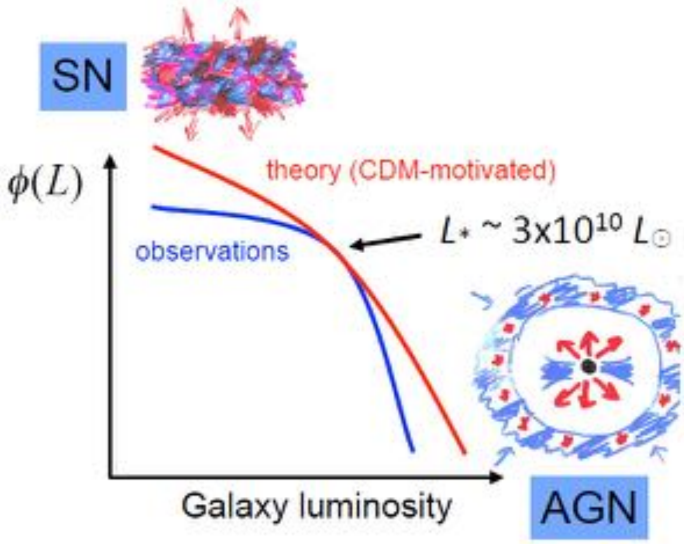
RUB



Behroozi+ 2013

RUHR-UNIVERSITÄT BOCHUM

RUB



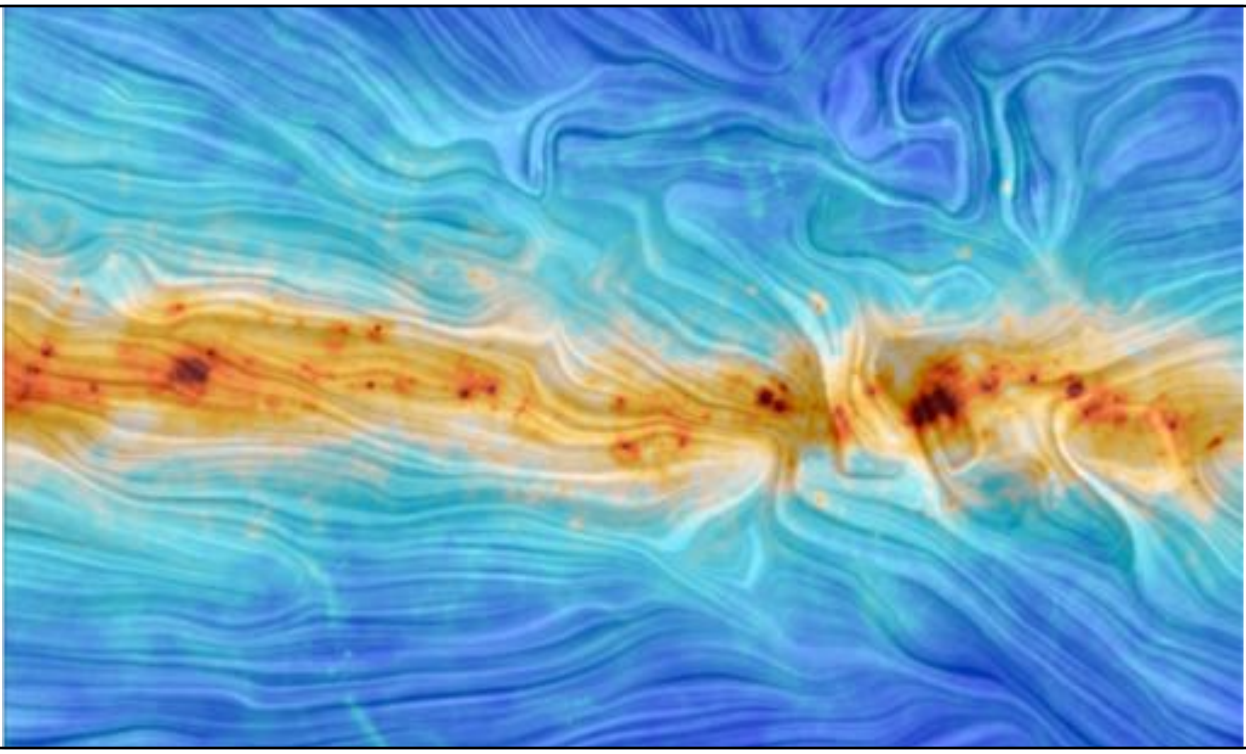
Silk 2013

Order in the chaos: magnetic field

- Field lines form **spiral patterns** with pitch-angles between 10° and 40° , even in flocculent and irregular galaxies.
- Turbulent fields are strongest in optical spiral arms.
- Regular fields are strongest in interarm regions, sometimes forming magnetic spiral arms (NGC6946), or at the inner edge of density-wave spiral arms (M51).

M51

(Fletcher et al. 2008)



RUHR-UNIVERSITÄT BOCHUM

Outline

1. Introduction/Motivation
2. Observational techniques
3. CR transport: galactic winds
4. Polarization and B-field in halos
5. Summary

1. Introduction

The more general topic:
Magnetic Fields and Cosmic Rays in Star-Forming Disk Galaxies

Why care?

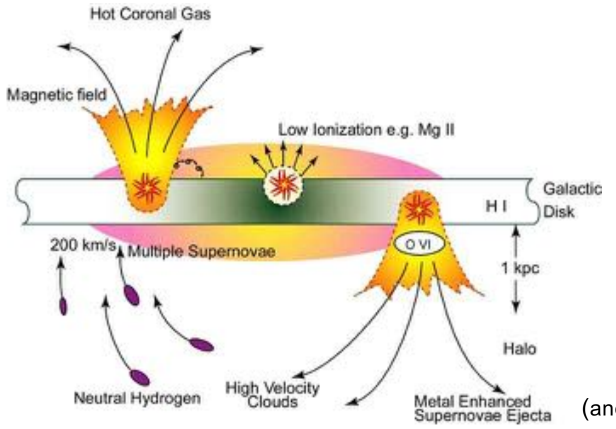
magnetic fields of galactic scales important in astrophysical contexts in particular in star formation, particle acceleration

the mere existence on a level of ~10 micro-Gauss (1nT) is considered a fundamental physics problem

acceleration and transport of Cosmic Rays, e.g. UHE CRs

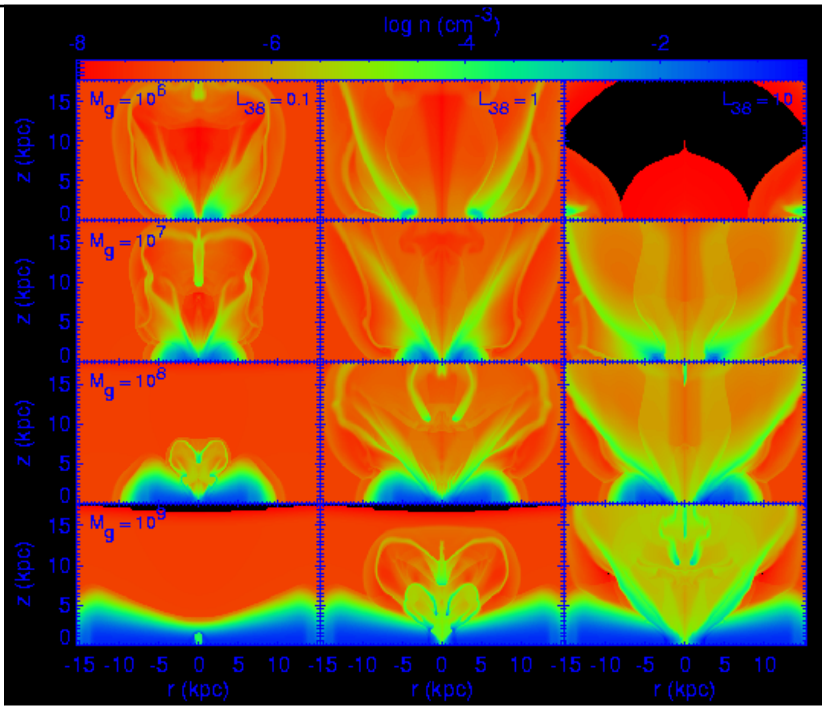
a somewhat „traditional“ view:

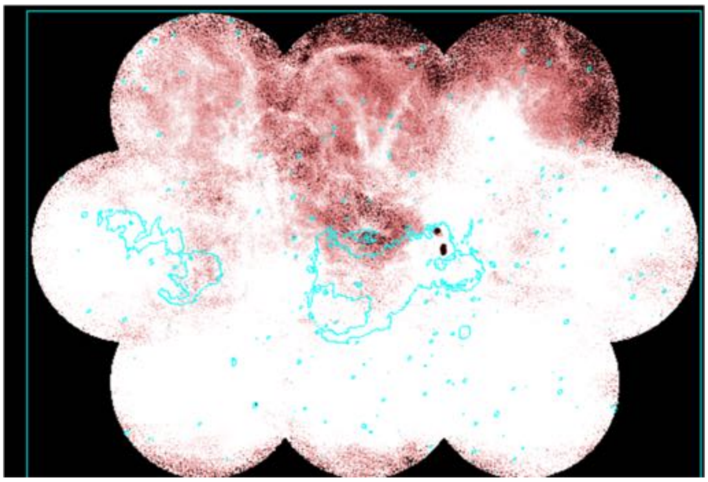
„chimney model“ (Norman & Ikeuchi)



(anonymous NASA artist)

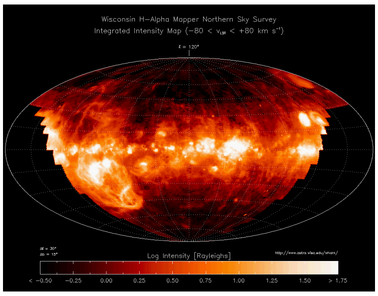
*F*errara & McLow

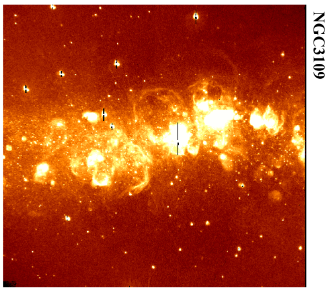


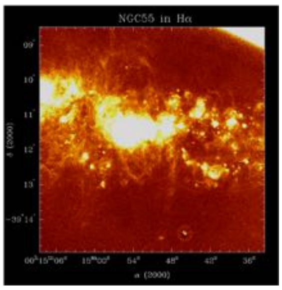


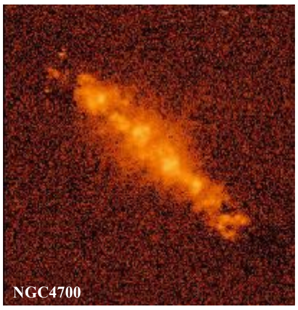
W3 chimney in DRAO HI Galactic Plane survey
(Univ. Calgary Website)

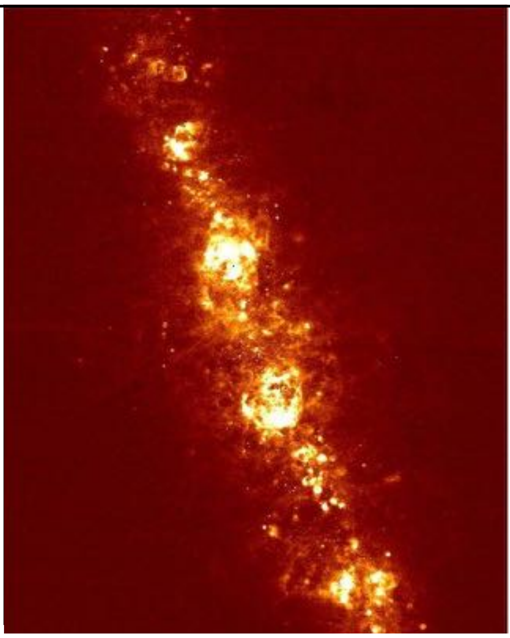
Diffuse ionized gas in galaxies







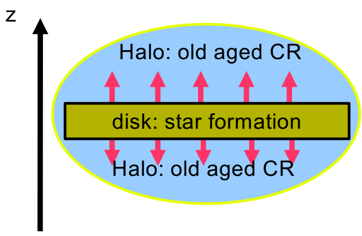


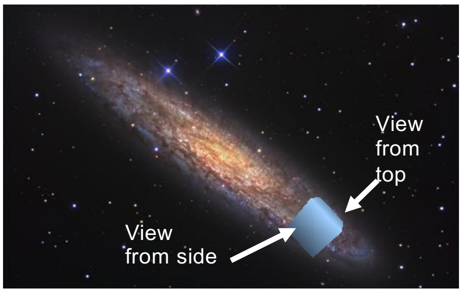


NGC4700 with HST/ACS

Simulations of the ISM

- Clustering of Supernovae => Breakout of the gas

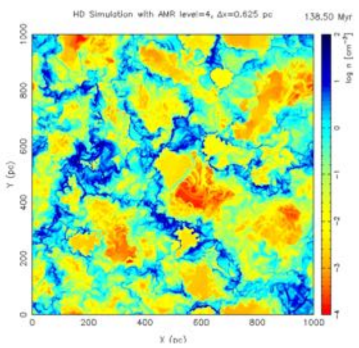


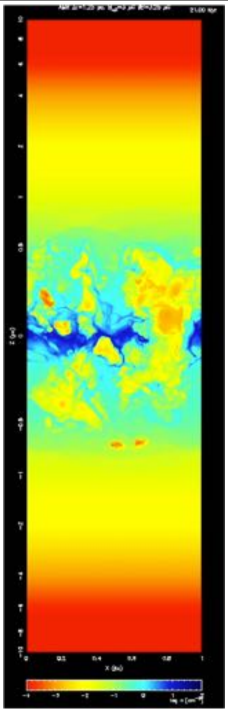


and a modern theoretical view:

multiphase ISM in simulations

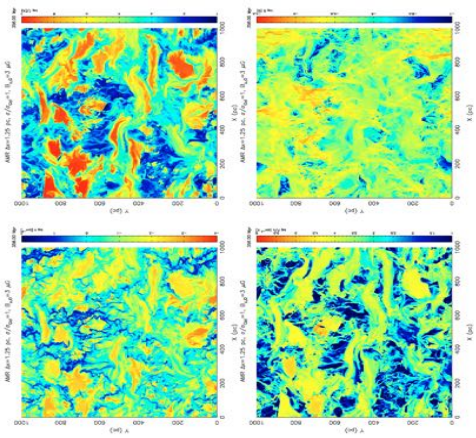
e.g. de Avillez & Breitschwerdt





view from top

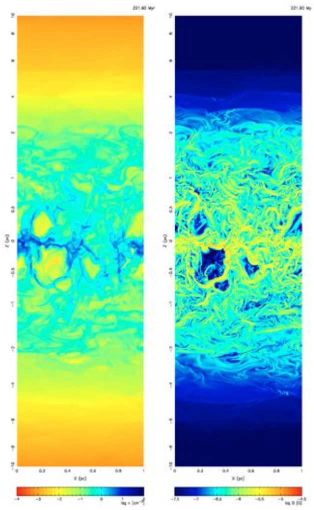
Density   Temperature



Pressure   Magnetic Field

view from side

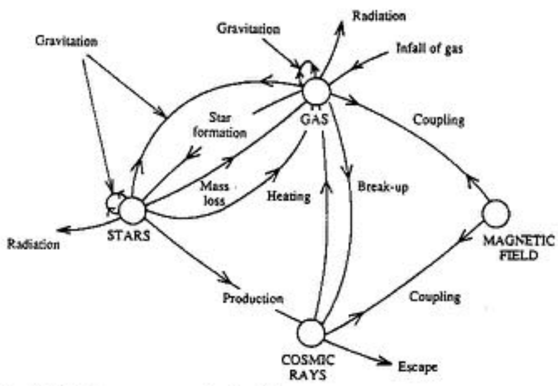
Density   Magnetic Field



Avillez et al. 2005

Processes in the interstellar medium

(from Taylor, Cambridge Univ. Press)

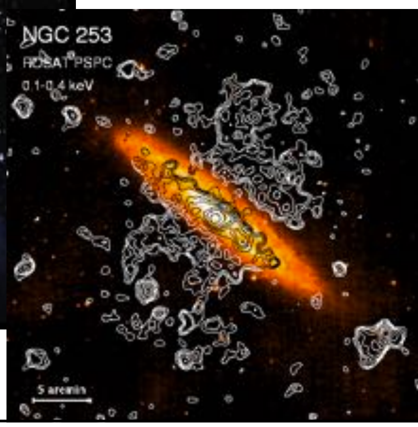


Magnetic Fields and Cosmic Rays contribute significantly to the energy density, or in other terms the pressure:

$U_{rad} \sim U_B \sim U_{CR} \sim U_{kin}$

RUHR-UNIVERSITÄT BOCHUM

NGC 253



Outflows needed to „shape“ galaxies

Letter

Nature **463**, 203-206 (14 January 2010) | doi:10.1038/nature08640; Received 8 September 2009; Accepted 5 November 2009

Bulgeless dwarf galaxies and dark matter cores from supernova-driven outflows

F. Governato[1], C. Brook[2], L. Mayer[3], A. Brooks[4], G. Rhee[5], J. Wadsley[6], P. Jonsson[7], B. Willman[9], G. Stinson[6], T. Quinn[1] & P. Madau[8]

RUHR-UNIVERSITÄT BOCHUM

recognition in cosmological context

RUB

Magnetic fields in cosmological simulations of disk galaxies

R. Pakmor, F. Marinacci, V. Springel

(Submitted on 9 Dec 2013 (v1), last revised 3 Feb 2014 (this version, v2))

Observationally, magnetic fields reach equipartition with thermal energy and cosmic rays in the interstellar medium of disk galaxies such as the Milky Way. However, thus far cosmological simulations of the formation and evolution of galaxies have usually neglected magnetic fields. We employ the moving-mesh code \textsc{Arepo} to follow for the first time the formation and evolution of a Milky Way-like disk galaxy in its full cosmological context while taking into account magnetic fields. We find that a prescribed tiny magnetic seed field grows exponentially by a small-scale dynamo until it saturates around $z = 4$ with a magnetic energy of about 10% of the kinetic energy in the center of the galaxy's main progenitor halo. By $z = 2$, a well-defined gaseous disk forms in which the magnetic field is further amplified by differential rotation, until it saturates at an average field strength of $\sim 6 \mu$G$ in the disk plane. In this phase, the magnetic field is transformed from a chaotic small-scale field to an ordered large-scale field coherent on scales comparable to the disk radius. The final magnetic field strength, its radial profile and the stellar structure of the disk compare well with observational data. A minor merger temporarily increases the magnetic field strength by about a factor of two, before it quickly decays back to its saturation value. Our results are highly insensitive to the initial seed field strength and suggest that the large-scale magnetic field in spiral galaxies can be explained as a result of the cosmic structure formation process.

ApJ 783, L20 (2014)

RUHR-UNIVERSITÄT BOCHUM

ApJ 777, L16 (2013)

SIMULATIONS OF DISK GALAXIES WITH COSMIC RAY DRIVEN GALACTIC WINDS

C. M. Booth[1], Oscar Agertz[2,1], Andrey V. Kravtsov[1,3,4], and Nickolay Y. Gnedin[5,1,3]

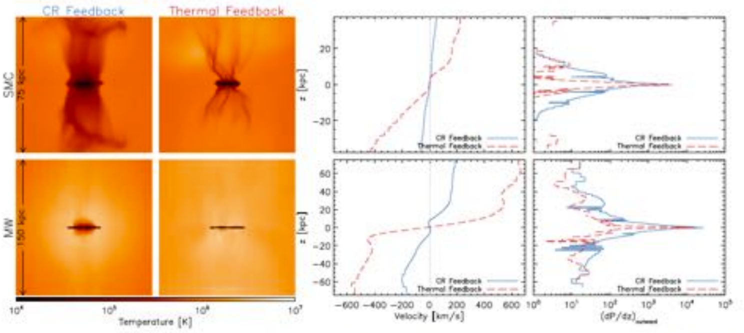
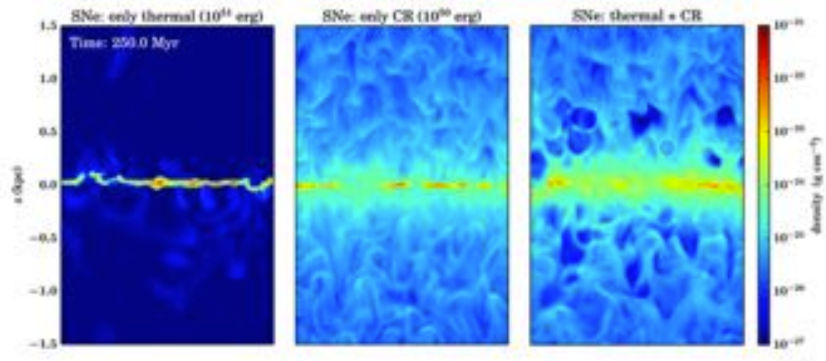


FIG. 3.— Edge-on maps of the temperature in a thin slice around the MW (*top panels*) and SMC galaxies (*bottom panels*) for both the thermal feedback *left panels*) and CR feedback (*right panels*). CR feedback has a large effect on the temperature structure of the halo gas. The plots show the median velocity (*left panels*) and outward pressure force (*right panels*) as a function of height from the disk for the same two simulations. All quantities are calculated in a cylinder of radius 3kpc, centered on the galactic disk. It is clear that the effect of the CRs is to increase the outward pressure forces in the halo by a factor of 3-5 at all z. This pressure gradient slowly accelerates the wind into the halo. The wind in the thermal feedback simulations is accelerated abruptly from the disk and maintains a constant velocity thereafter.

LAUNCHING COSMIC-RAY-DRIVEN OUTFLOWS FROM THE MAGNETIZED INTERSTELLAR MEDIUM

Philipp Girichidis[1], Thorsten Naab[1], Stefanie Walch[2], Michał Hanasz[3], Mordecai-Mark Mac Low[4,5], Jeremiah P. Ostriker[6], Andrea Gatto[1], Thomas Peters[1], Richard Wünsch[7], Simon C. O. Glover[5], Ralf S. Klessen[5], Paul C. Clark[8], and Christian Baczynski[5] — Hide full author list

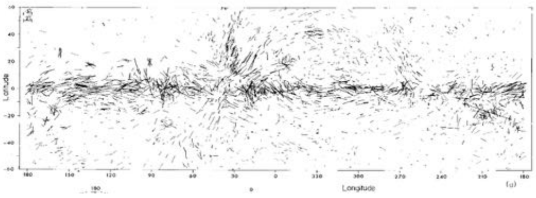
Published 2016 January 6 •
The Astrophysical Journal Letters, Volume 816, Number 2



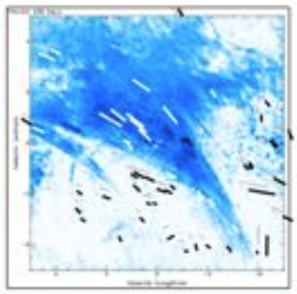
2. Observational Techniques

- **Optical and infrared polarization (dust grain alignment)**
- **Zeeman splitting**
- **Total and polarized radio synchrotron**
- **Faraday rotation and depolarization**

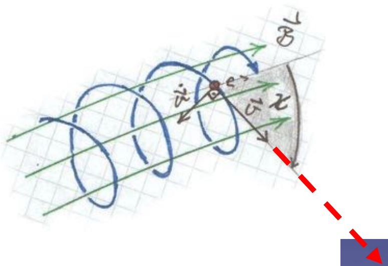
magnetic field direction correlates with small scale structure
in the cold interstellar medium
"Cratcher-Cloud" from Galactic Plane Survey
(Australia Telescope Compact Array data by McClure-Griffiths et al. 2006)

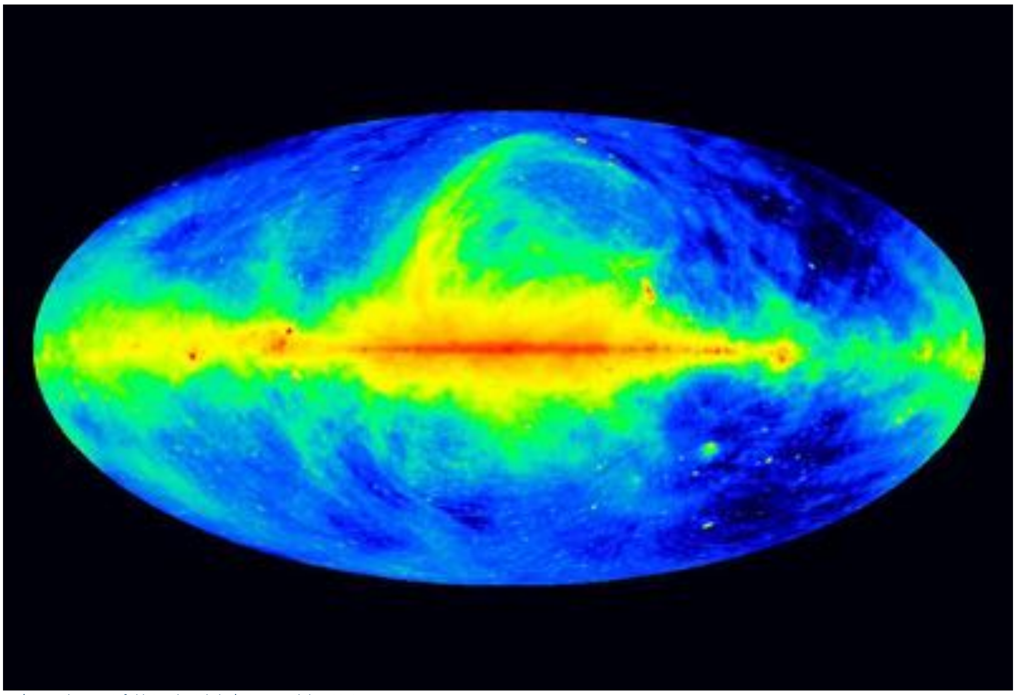


Mathewson & Ford 1970



Synchrotron radiation of relativistic electrons





408MHz Jodrell-Parkes-Effelsberg

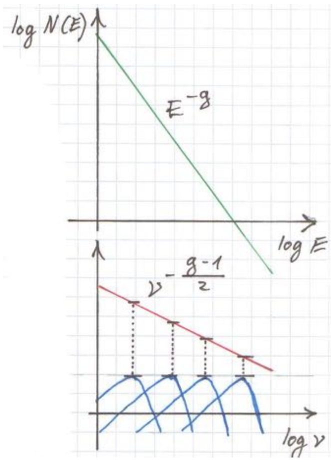
Spectrum of the ensemble:

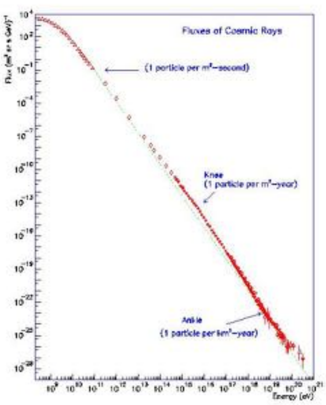
Convolution of single spectra with energy distribution

$$N(E)\cdot dE \propto E^{-g}\cdot dE$$

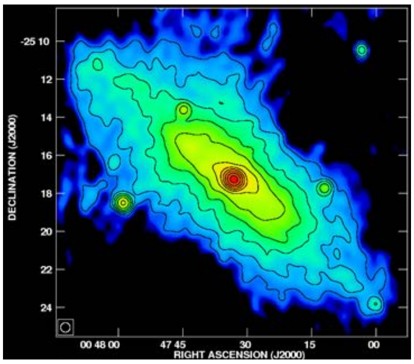
$$g = 2\cdot\alpha + 1$$

$$I_\nu \propto B_\perp^{1+\alpha}\cdot\nu^{-\alpha}$$

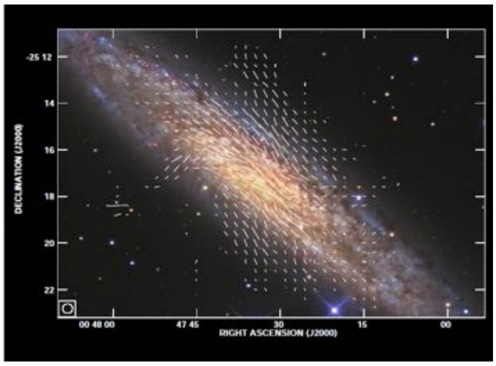




What we can measure: synchrotron emission from CR electrons



NGC 253 radiocontinuum study at 3, 6, 20, 90 cm



(Heesen, Krause, Beck, Dettmar 2009 A&A)

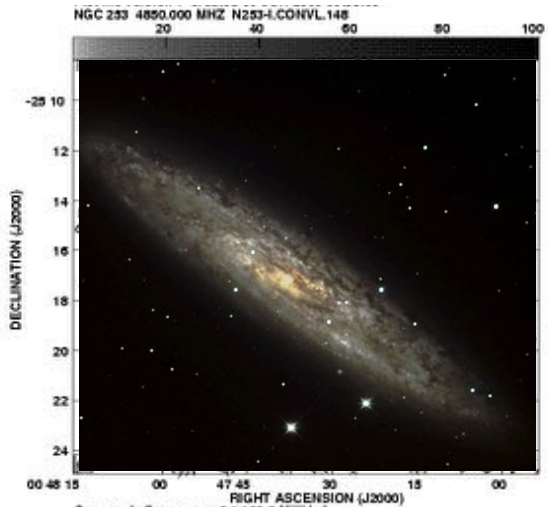
Polarized emission (and angles):

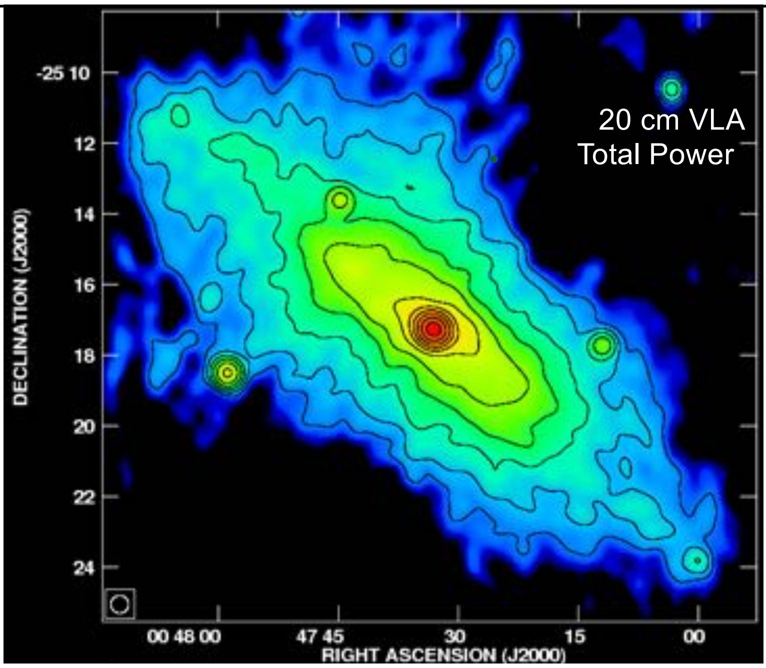
$I \propto \int n_{CR} B_{\perp}^{1+\alpha} dl$

Faraday rotation measures of the diffuse polarized emission:

$RM \propto \int n_e B_{\parallel} dl$

Multifrequency study of NGC 253 (Heesen et al 2009)



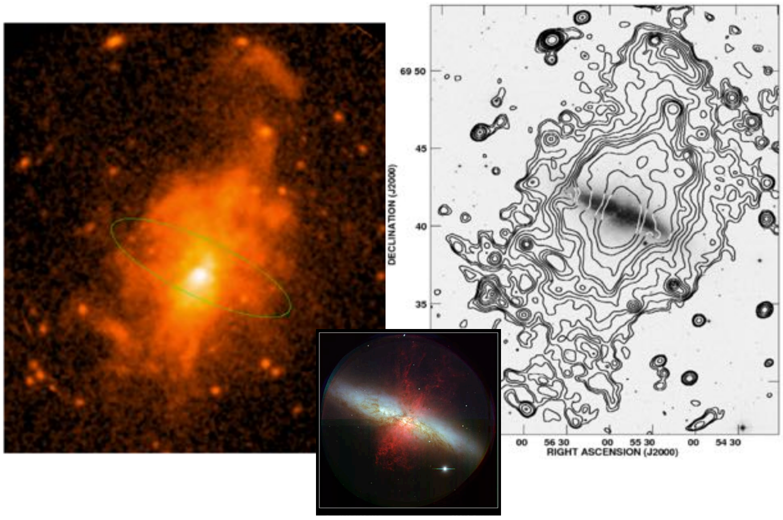


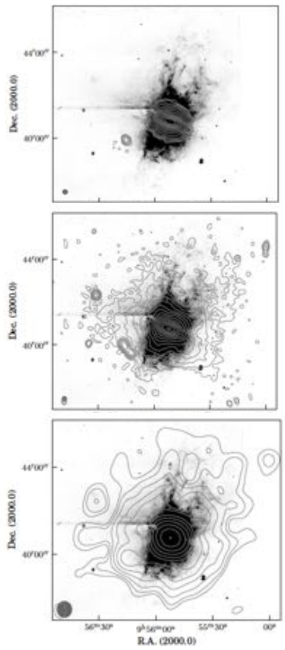
3. CR transport and galactic winds

the prototypical galactic wind M82

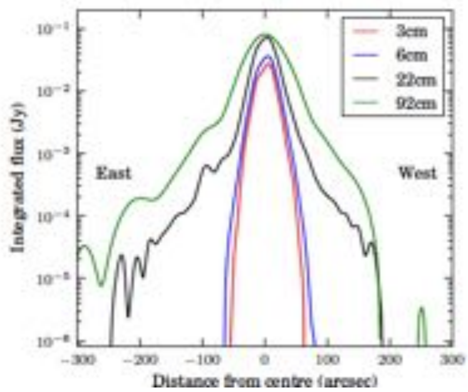
Subaru

M82 in X-rays / XMM (Wezgowiec, et al. in prep.)





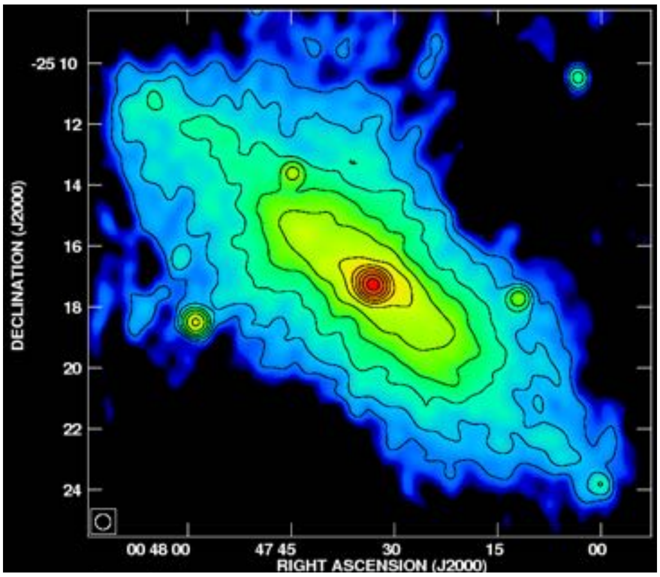
cosmic ray transport in M82



Adebahr et al. 2013, A&A

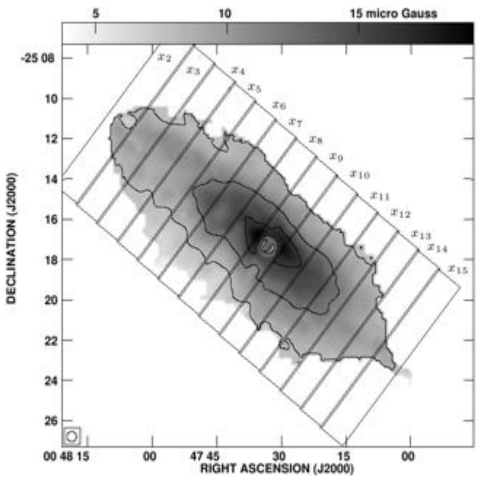
„Pilot“ study: NGC253

(Heesen, Krause, Beck, Dettmar 2009 A&A)



NGC 253 radiocontinuum study at 3, 6, 20, 90 cm

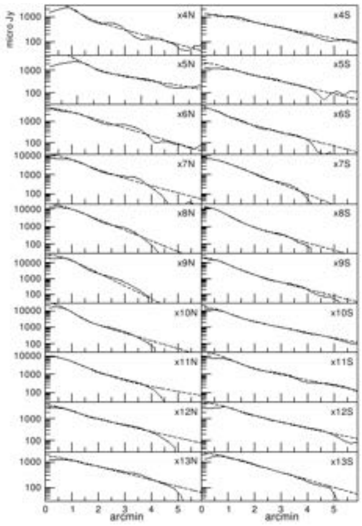
Total magnetic field strength



local magnetic field strength

local Synchrotron-lifetime

equipartition magnetic field strength: $B \propto L_\nu^{1/(3+\alpha_{\rm nt})}$



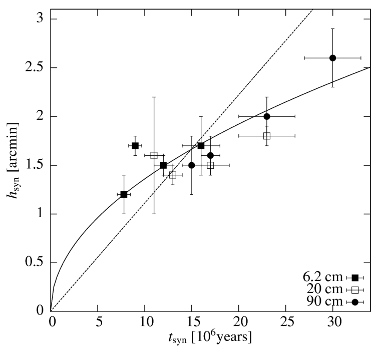
total power emission

distance from the major axis: z

Exponential distribution with scaleheight: h perpendicular to disk: z

typical scaleheight ~ 1.7 kpc

Scaleheight vs. Synchrotron- lifetime



total power scaleheight

Synchrotron-lifetime

Cosmic ray propagation

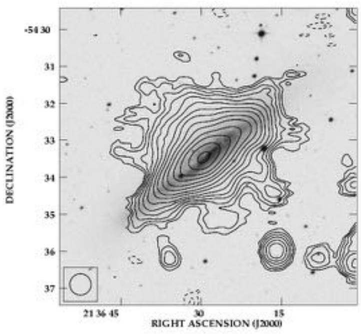
$$v_{\mathrm{e}} = \frac{3 + \alpha_{\mathrm{nt}}}{2} \frac{\Delta h_{\mathrm{e}}}{\Delta t_{\mathrm{Syn}}}$$

$$\bar{v}_{\lambda 6.2} = (280 \pm 40)\ \mathrm{km\,s^{-1}}$$

close to escape velocity!

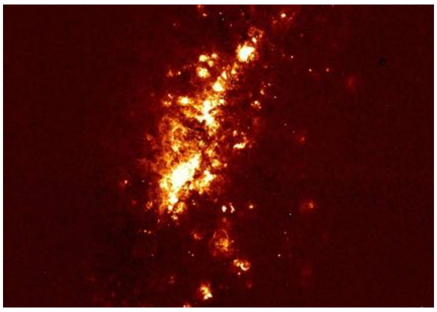
…the lucky coincidence

NGC 7090

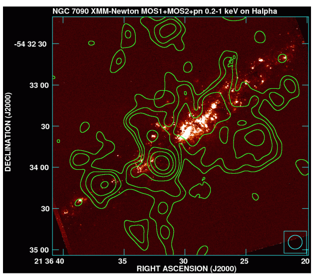


Dahlem & Ehle

ATCA



Rossa Dettmar Dahlem ACS/HST



Dettmar & Wezgowiec / XMM

38

Example: ATCA Observations

22 + 6 cm, radio continuum polarimetry

~160 hr at 22 cm and ~60 hr at 6 cm each

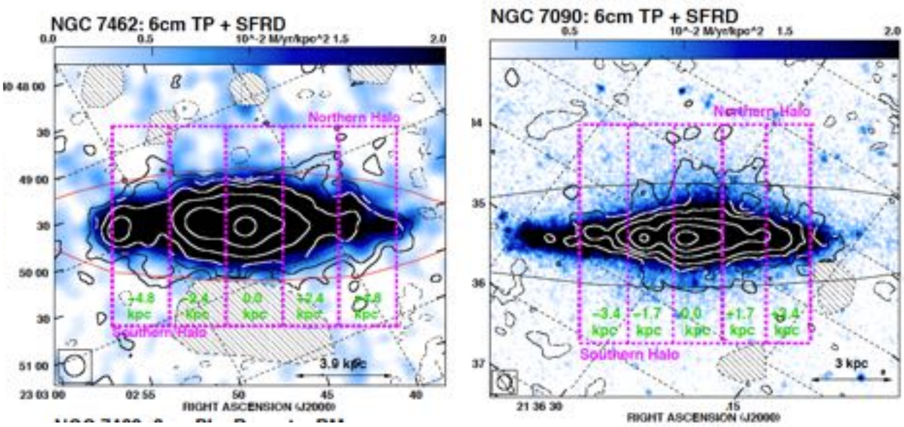
rms: ~30 μJy/beam at 22 cm and ~15 μJy/beam at 6 cm

Cleaned with CASA multi-scale CLEAN

N7090

N7462

analysis of CR transport (ATCA 6&20cm)



Heesen, Dettmar, Krause et al. 2016 MNRAS 458, 332

“clean non-thermal emission”: 1D Modelling of CR–Transport

N(E, z): Cosmic Ray Electron number (column) density

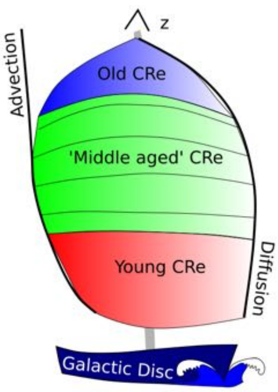
Advection: $$\frac{\partial N(E,z)}{\partial z} = \frac{1}{V}\left\{\frac{\partial}{\partial E}\left[b(E)N(E,z)\right]\right\}$$

Diffusion: $$\frac{\partial^2 N(E,z)}{\partial z^2} = \frac{1}{D}\left\{\frac{\partial}{\partial E}\left[b(E)N(E,z)\right]\right\}$$

CRe losses: $$-\left(\frac{\mathrm{d}E}{\mathrm{d}t}\right) = b(E) = \frac{4}{3}\sigma_{\mathrm{T}}c\left(\frac{E}{m_{\mathrm{e}}c^2}\right)^2(U_{\mathrm{rad}} + U_{\mathrm{B}})$$

iC losses → U_{rad}; synchrotron radiation → U_{B}

CRE transport: SPINNAKER



- **Sp**ectral **In**dex **N**umerical **A**nalysis of **K**(c)osmic-ray **E**lectron **R**adio-emission
- www.github.com/vheesen/Spinnaker

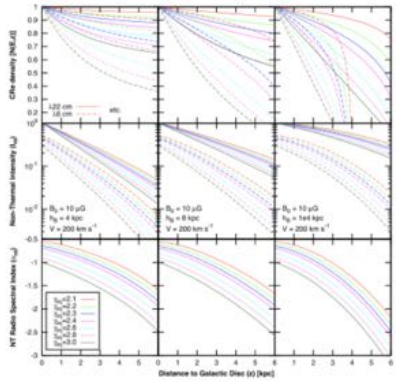
Advection models

h_B = 4 kpc h_B = 8 kpc h_B = 1e4 kpc

N(E,z)

$I_{nt}(z)$

α_{nt}



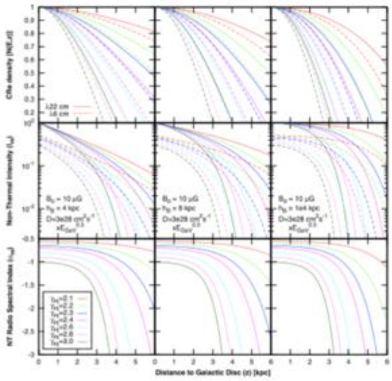
Diffusion models

h_B = 4 kpc h_B = 8 kpc h_B = 1e4 kpc

N(E,z)

$I_{nt}(z)$

α_{nt}



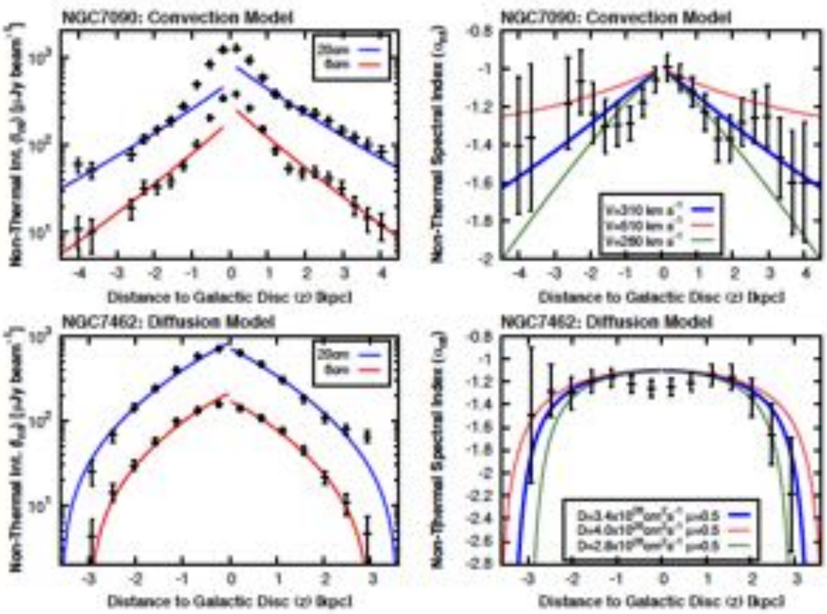


Table 2. Observation details for the galaxies presented in this paper.

Galaxy	Band[a]	ν[b] (GHz)	Telescope[c]	Configuration[d]	Project[e]	Time[f] (h)	Date[g]	Notes[h]	Reference[i]
NGC 55	*L*	1.37	ATCA	750D	C287	8.7	1993 Aug 1	Mosaic	17
...	...	...	...	375	C287	11.2	1995 Jan 12	...	...
...	...	...	...	750A	C287	11.1	1995 Oct 25	...	...
...	...	...	...	H75	C1341	5.0	2005 Jul 17	Mosaic	This work
...	...	...	...	EW352	C1341	9.4	2005 Oct 7	...	...
...	*C*	4.80	...	375	C287	3.6	1994 Mar 29	Mosaic	17
...	...	...	...	375	C287	10.2	1994 Mar 30	...	...
...	...	...	...	375	C287	7.8	1994 Mar 31	...	...
...	...	...	...	375	C287	12.5	1994 Nov 23	...	...
...	...	...	...	750A	C287	5.1	1995 Mar 1	...	...
...	...	...	...	375	C287	5.3	1995 Aug 16	...	...
...	...	...	...	375	C287	10.2	1995 Nov 24	...	...
...	...	4.67	...	EW352	C1974	7.6	2008 Nov 22	...	This work
...	...	...	...	EW364	C1974	9.9	2009 Feb 13	...	...
...	*C*	5.60	...	H168	C1974	7.6	2010 Mar 27	...	...
...	*C*	4.80	Parkes	single-dish	P697	16.0	2010 Oct 7	Merged	...
NGC 253	*L*	1.46	VLA	B+C+D	AC278	4.1	1990 Sep–1991 Mar	Mosaic	2
...	*C*	4.86	...	D	AH844	35.8	2004 Jul 4–24	Mosaic	10
...	...	4.85	Effelsberg	single-dish	N/A	N/A	1997	Merged	...
NGC 891	*L*	1.39	WSRT	Multiple	R02B	240	2002 Aug–Dec		13
...	*C*	4.86	VLA	D	AA94	11.2	1988 Aug 29		16
...	...	4.85	Effelsberg	single-dish	44–95	9.1	1996 Feb–Aug		6
NGC 3044	*L*	1.49	VLA	B	AI28	3.1	1986 Aug 1		This work
...	...	...	...	C	AI23	0.8	1985 Jul 25		11
...	...	...	...	D	AI31	1.1	1987 Apr 28/30		...
...	*C*	4.86	...	C	AB676	0.8	1993 Jun 13		4
...	...	...	...	D	AM573	1.1	1997 Nov 6		This work
...	...	...	...	D	AI31	1.0	1987 Apr 28		11
NGC 3079	*L*	1.66	VLA	B	BS44	1.0	1997 Mar 8		This work
...	...	1.41	...	CD	BS44	2.4	1997 Oct 2		...
...	...	1.43	...	C	AB740	1.3	1996 Feb 17		...
...	*C*	4.71	...	C	AC277	3.9	1990 Dec 9		3
...	...	4.86	...	D	AD177	2.5	1986 Jan 16		This work
NGC 3628	*L*	1.49	VLA	CD	AS300	4.3	1988 Mar 25		14
...	...	...	...	D	AS300	8.4	1987 Apr 7		...
...	*C*	4.86	...	D	AK243	7.7	1991 Mar 28		7
NGC 4565	*L*	1.49	VLA	B	AS326	3.8	1988 Jan 29		16
...	...	1.48	...	D	AS326	10.6	1988 Aug 28		...
...	*C*	4.86	...	D	AK424	3.4	1996 Sep 28		6
NGC 4631	*L*	1.37	WSRT	maxi-short	N/A	6.0	2003 Apr 3		1
...	*C*	4.86	VLA	D	AH369	12.1	1989 Nov 22/26	Mosaic	9
...	...	...	...	D	AD896	4.3	1999 Apr 14	Mosaic	12
...	...	4.85	Effelsberg	single-dish	55–94	6.3	1996 Feb–Aug	Merged	6
NGC 4666	*L*	1.43	VLA	CD	AD346	3.5	1994 Nov 20		5
...	...	1.49	...	D	AS199	0.2	1984 Aug 31		This work
...	*C*	4.86	...	D	AD326	12.5	1993 Dec 20/24		5
NGC 5775	*L*	1.49	VLA	B	AI0028	3.2	1986 Aug 1		8
...	...	1.48	...	B	AB492	1.2	1989 Aug 4		...
...	...	1.49	...	C	AH368	3.6	1990 Nov 19/24		...
...	...	...	...	D	AI31	1.9	1987 Apr 27/30		11
...	*X*	8.45	...	D	AD455	13.4	2001 Dec 14		15

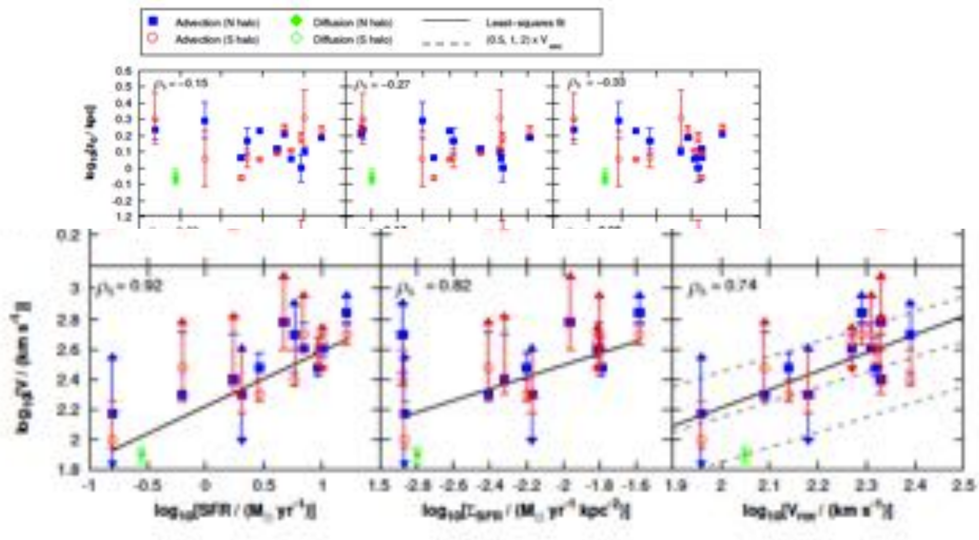


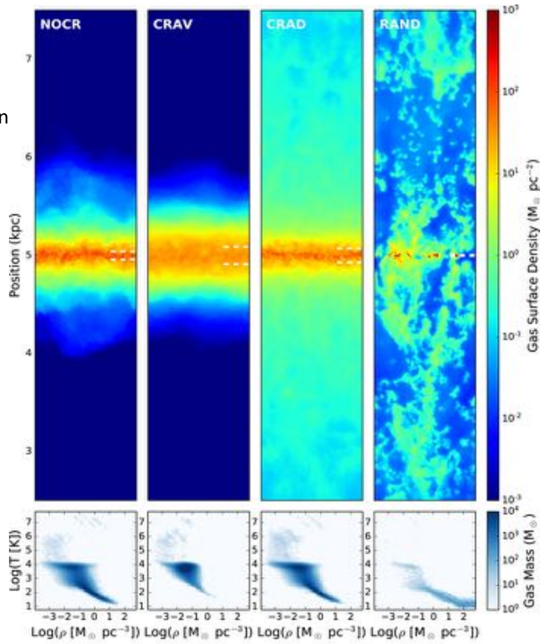
Figure 5. Parameter studies in log-log diagrams as function of SFR, SFR surface density (Σ_{SFR}) and rotation speed V_{rot}. *Top panels:* non-thermal intensity scale height (z_{B}) at 5 GHz (8.5 GHz for NGC 5775) of the thick radio disc. *Middle panels:* magnetic field scale height (h_B) of the thick radio disc. *Bottom panels:* Advection speed (V), where solid lines show least-squares fits. In the bottom right panel the dashed lines show (0.5, 1, 2)×V_{esc}. In each panel, we also present Spearman's rank correlation coefficient, ρ_s, which we derived from values that have both an upper and lower limits.

Heesen+ 2018 MNRAS 476, 158

CRAV (identical to NOCR but 10% of the SN energy in CR energy. The remaining 90% is added as thermal energy. The CR energy can advect with the gas

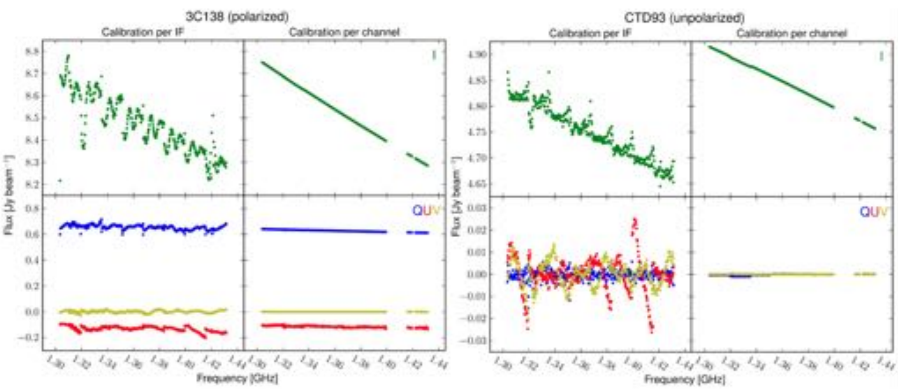
CRAD is identical to CRAV, but with *anisotropic* instead of isotropic CR diffusion (Pakmor et al. 2016a). The diffusion coefficient in this model is $\kappa = 10^{28}$ cm² s⁻¹ parallel to the magnetic field and zero in all transverse directions.

Christine M. Simpson et al. 2016 ApJL 827 L29

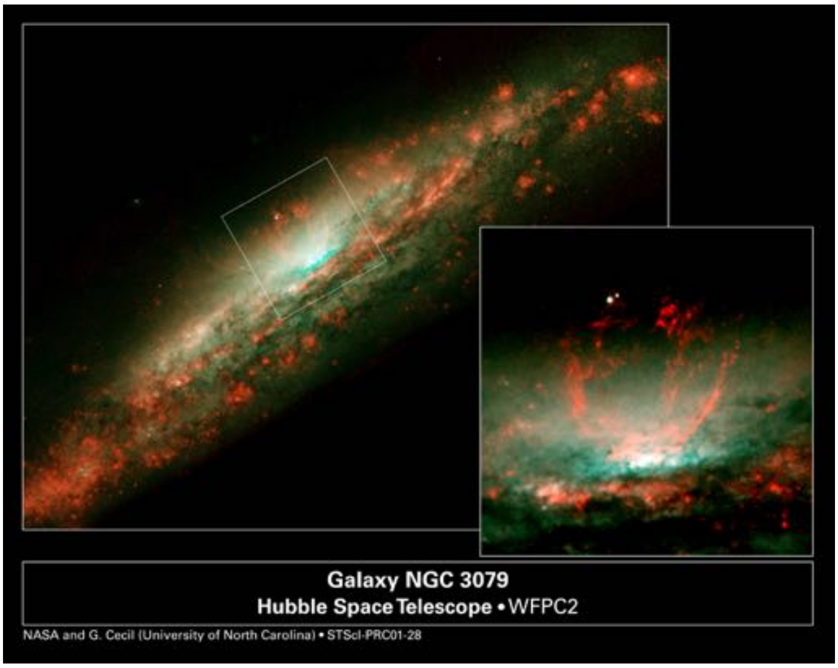


4. Receivers and B-field in halos

example: WSRT multichannel receiver



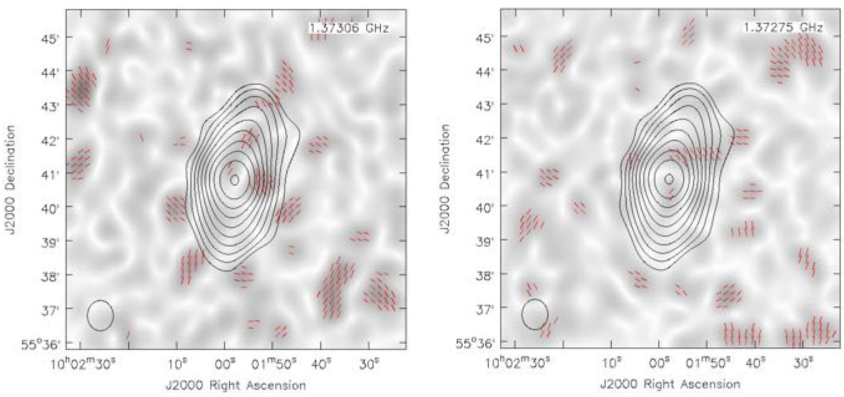
(Björn Adebahr, PhD thesis, Bochum 2013)



Starburst galaxy NGC 3079

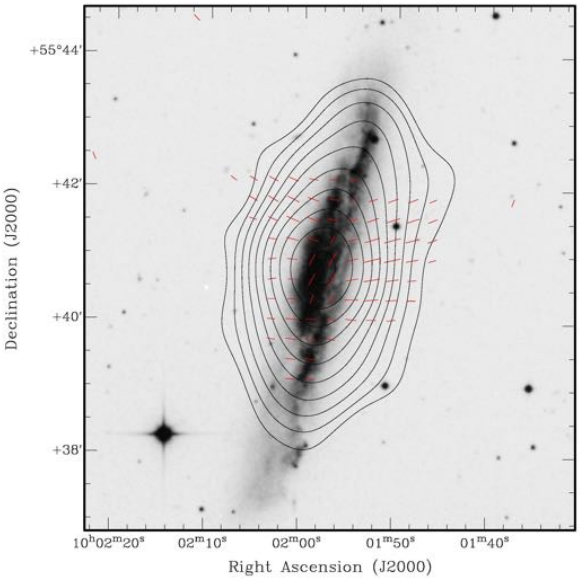
New technique: Rotation Measure Synthesis

WSRT observations of NGC3079



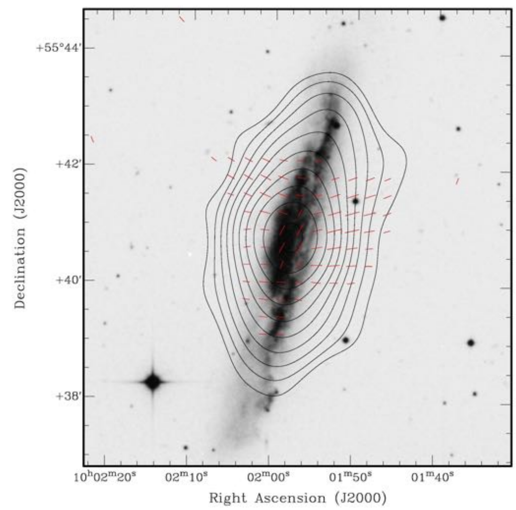
Carlos Sotomayor (PhD Bochum 2014)

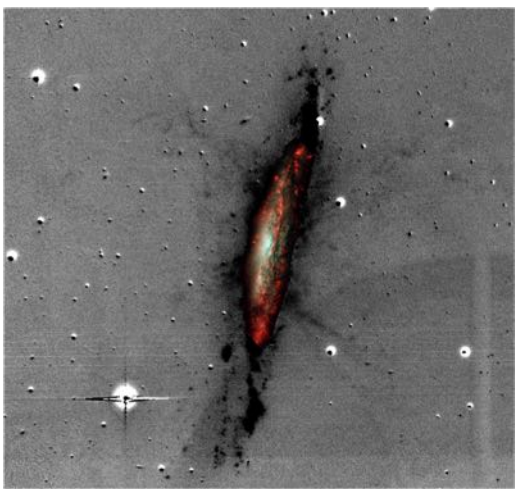
WSRT observations of NGC3079



N3079 (WRST)

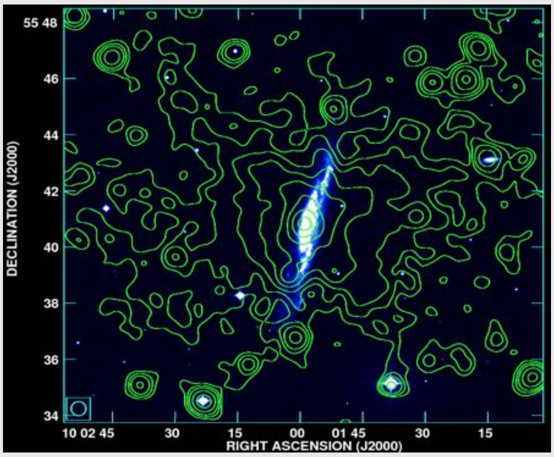
H_alpha

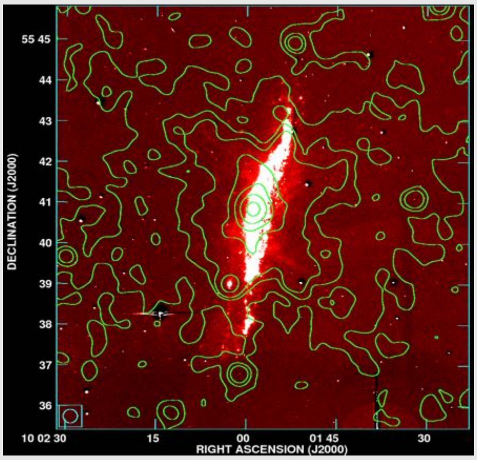




C. Sotomayor (PhD Bochum 2014); D.J. Bomans, A. Miskolczi

X-ray emission

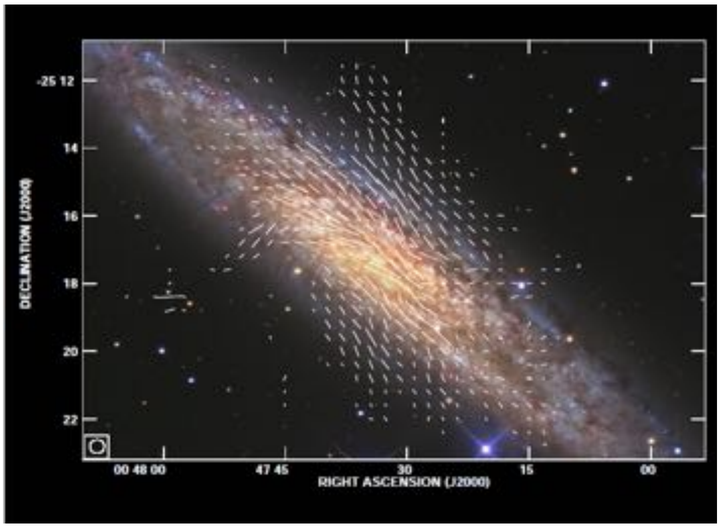




NGC 3079 soft X-ray image based on XMM-Newton archives (M. Wezgowiec).

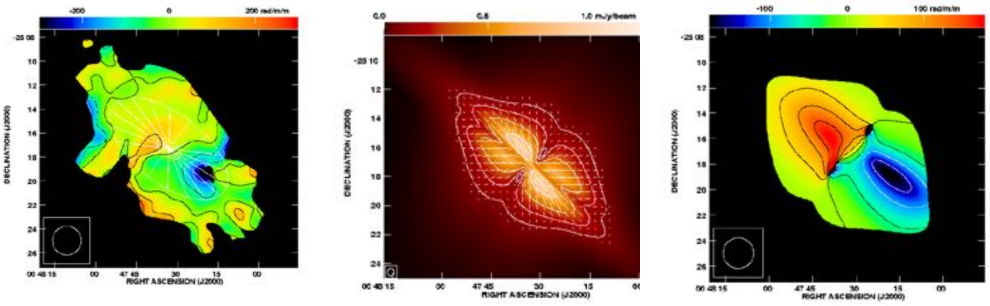
18 ks of clean pn data allows detailed spectral analysis.

NGC 253 radiocontinuum study at 3, 6, 20, 90 cm

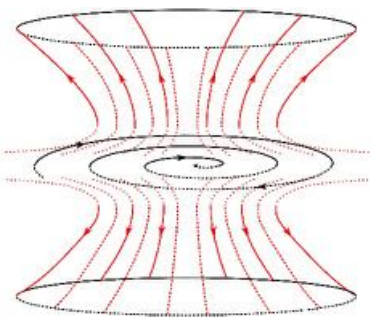


Heesen, Krause, Beck, Dettmar 2009 A&A 494, 563 & 506, 1013

Magnetic field structure from rotation measure analysis

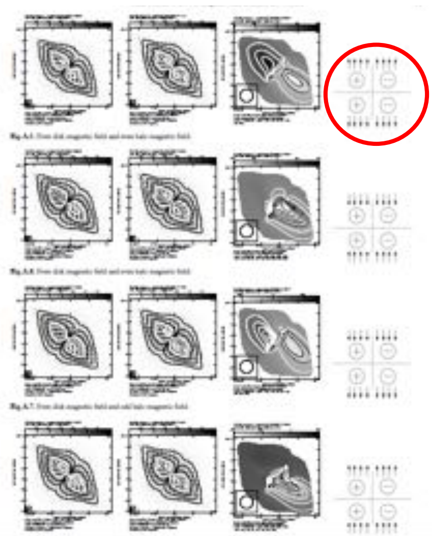


Magnetic field structure from rotation measure analysis



two component model for B

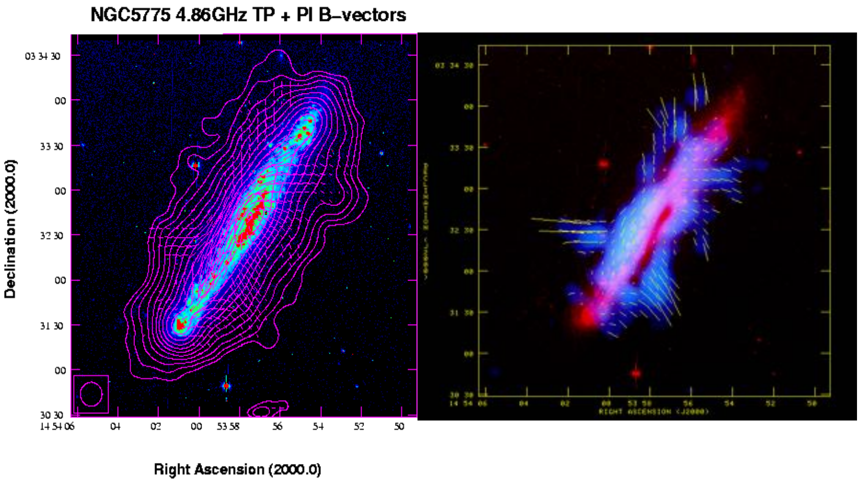
Heesen, Krause, Beck, Dettmar 2009 A&A



RUHR-UNIVERSITÄT BOCHUM

RUB

NGC 5775 comparison at three wavelengths



Soida, Krause, Dettmar, Urbanik A&A 2011
Tüllmann, Dettmar, Soida, et al. A&A, 2000 364,L36

RUHR-UNIVERSITÄT BOCHUM

RUB

a more general description of B:

Analytical models of X-shape magnetic fields in galactic halos

Katia Ferrière[1] and Philippe Terral[1]

[1] IRAP, Université de Toulouse, CNRS, 9 avenue du Colonel Roche, BP 44346, F-31028 Toulouse Cedex 4, France

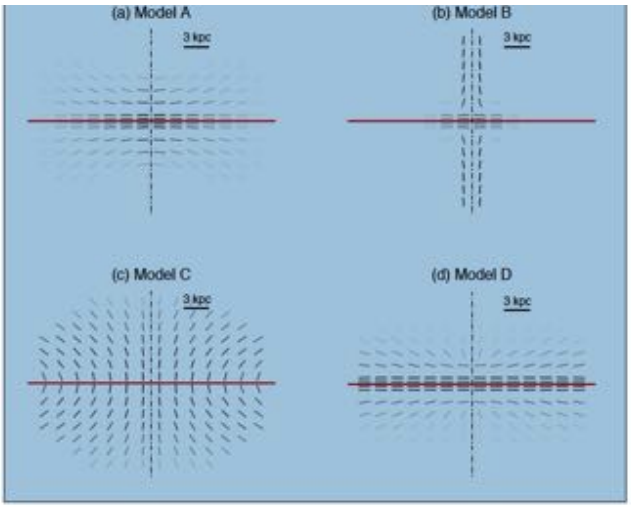
Received ; accepted

ABSTRACT

Context. External spiral galaxies seen edge-on exhibit X-shape magnetic fields in their halos. Whether the halo of our own Galaxy also hosts an X-shape magnetic field is still an open question.
Aims. We would like to provide the necessary analytical tools to test the hypothesis of an X-shape magnetic field in the Galactic halo.
Methods. We propose a general method to derive analytical models of divergence-free magnetic fields whose field lines are assigned a specific shape. We then utilize our method to obtain four particular models of X-shape magnetic fields in galactic halos. In passing, we also derive two particular models of predominantly horizontal magnetic fields in galactic disks. All our field models have spiraling field lines with spatially varying pitch angle.
Results. Our four halo field models do indeed lead to X patterns in synthetic synchrotron polarization maps. Their precise topologies can all be explained by the action of a wind blowing outward from the galactic disk or from the galactic center. In practice, our field models may be used for fitting purposes or as inputs to various theoretical problems.

Key words. Galaxies: magnetic fields – galaxies: halos – galaxies: spirals – Galaxy: halo – Galaxy: disk – ISM: magnetic fields

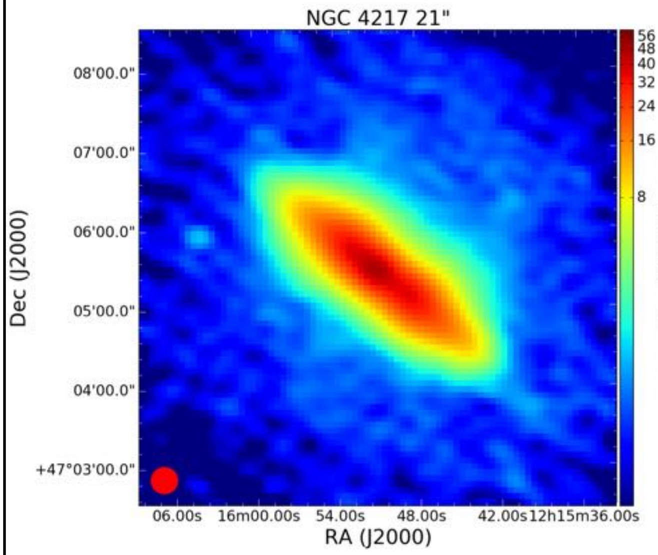
RUHR-UNIVERSITÄT BOCHUM

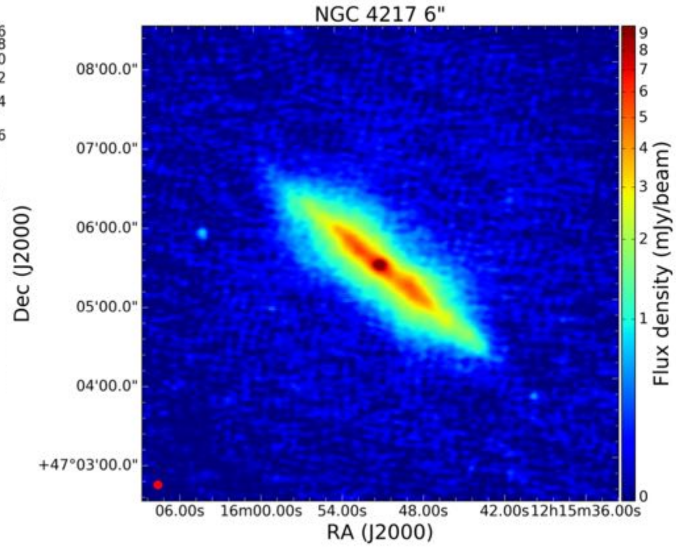


RUHR-UNIVERSITÄT BOCHUM

LOFAR HBA at Jülich (FZ Jülich- RU Bochum)

example LOFAR: LoTTS survey





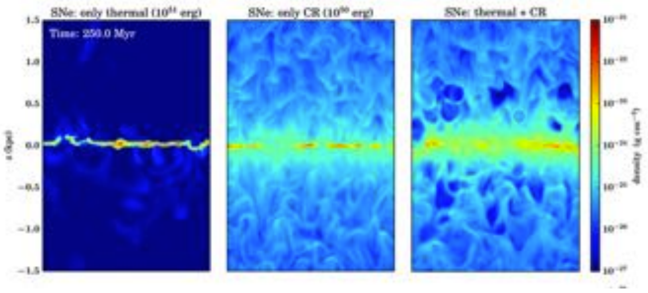
~0.1 mJy rms noise, 0.46Jy total flux (A. Miskolczi)

Cosmic ray-driven winds

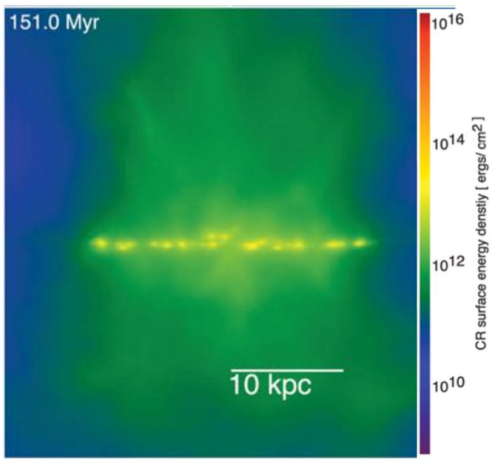
LAUNCHING COSMIC-RAY-DRIVEN OUTFLOWS FROM THE MAGNETIZED INTERSTELLAR MEDIUM

Philipp Girichidis[1], Thorsten Naab[1], Stefanie Walch[2], Michał Hanasz[3], Mordecai-Mark Mac Low[4,5], Jeremiah P. Ostriker[6], Andrea Gatto[1], Thomas Peters[1], Richard Wünsch[7], Simon C. O. Glover[5], Ralf S. Klessen[5], Paul C. Clark[8], and Christian Baczynski[5] —Hide full author list

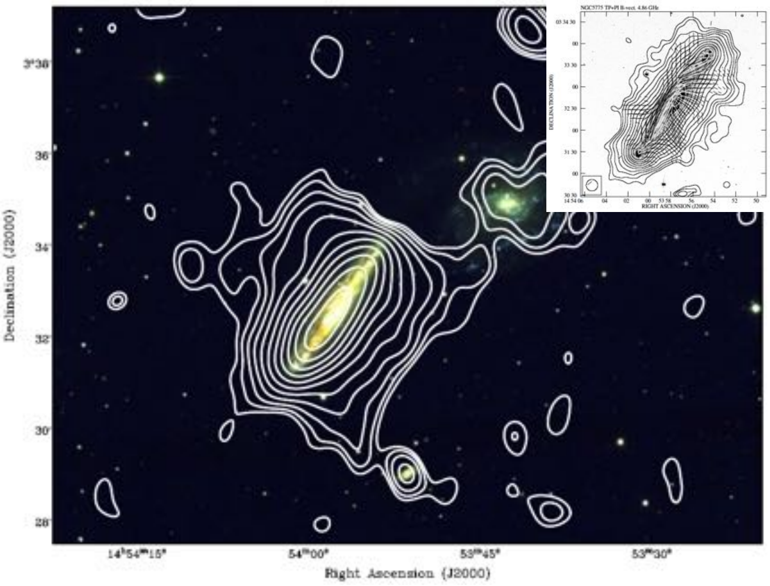
Published 2016 January 6 • © 2016. The American Astronomical Society. All rights reserved.
The Astrophysical Journal Letters, Volume 816, Number 2



Salem & Bryan (2014)



LOFAR HBA 10hrs 118-192 MHz (Heald, Shridar + LOFAR MKSP)



CHANGES:
Continuum HAlos in Nearby Galaxies
- an Evla Survey

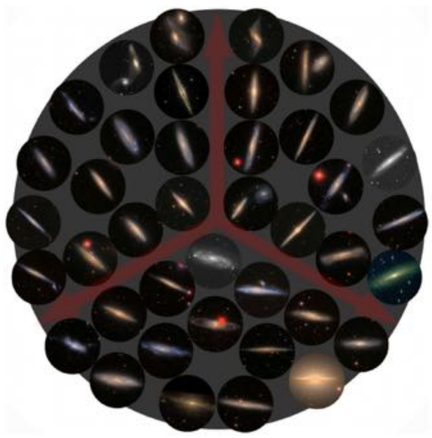
PI: Judith Irwin, Kingston (ONT/CANADA)

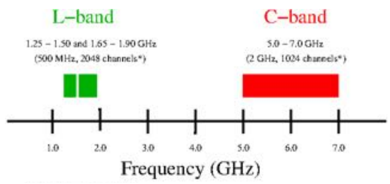
35 edge-on galaxies

inclination > 75 deg
DEC > 25 deg
4 arcmin > D < 15 arcmin
flux > 23 mJy

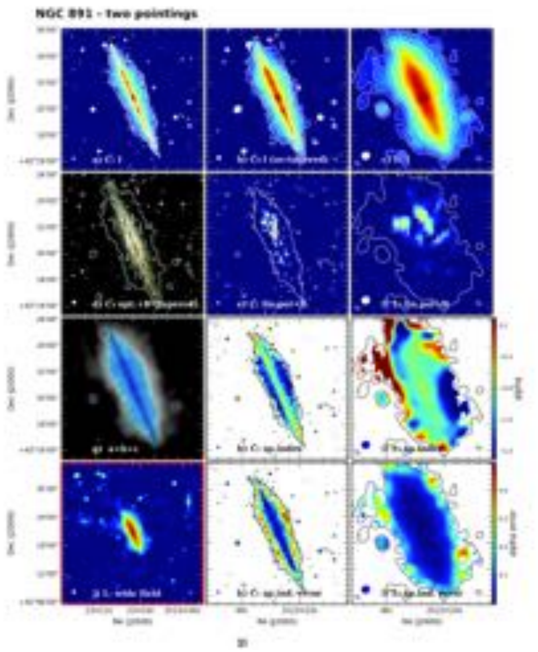
+ a few well studied larger object

Large proposal 405 hours granted (RSRO)

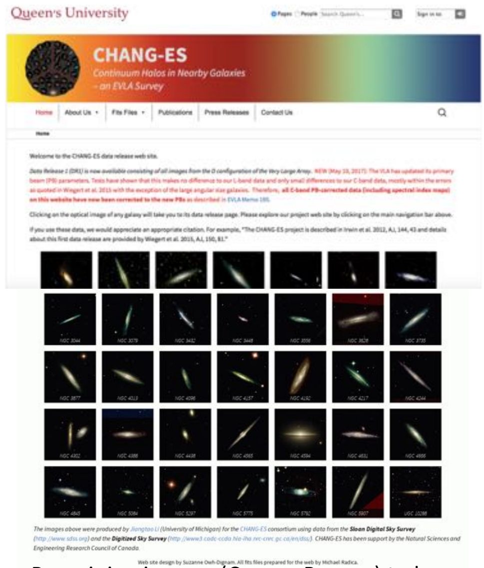




Wiegert et al. AJ 150, 81 (2015) D-array C & L band

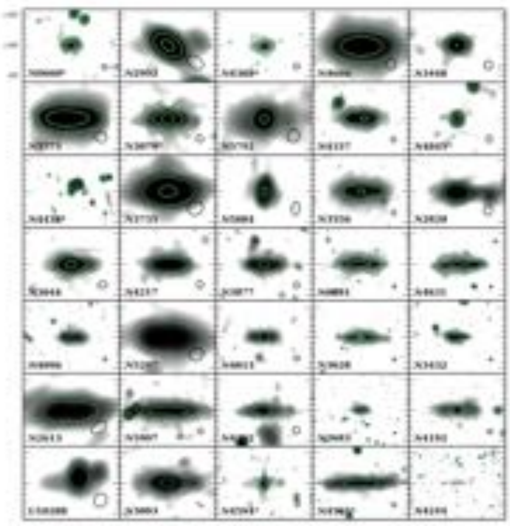


queensu.ca/changes

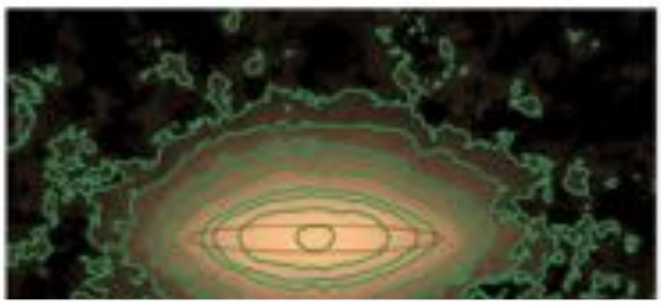


Remaining images (C array B array) to be released in 2019

sorted by SFR at common distance



„averaged“ radio continuum halo



The Astrophysical Journal Letters, 799:L10 (6pp), 2015 January 20 doi:10.1088/2041-8205/799/1/L10

AXIAL RATIO OF EDGE-ON SPIRAL GALAXIES AS A TEST FOR BRIGHT RADIO HALOS

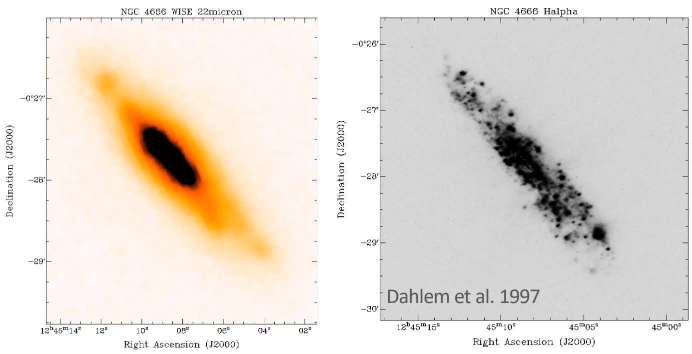
J. Singal[1], A. Kogut[2], E. Jones[1], and H. Dunlap[1]
[1] Physics Department, University of Richmond 28 Westhampton Way, Richmond, VA 23173, USA; jsingal@richmond.edu
[2] Code 665, NASA Goddard Space Flight Center Greenbelt, MD 20771, USA
Received 2014 August 28; accepted 2014 December 24; published 2015 January 19

ABSTRACT

We use surface brightness contour maps of nearby edge-on spiral galaxies to determine whether extended bright radio halos are common. In particular, we test a recent model of the spatial structure of the diffuse radio continuum by Subrahmanyan & Cowsik which posits that a substantial fraction of the observed high-latitude surface brightness originates from an extended Galactic halo of uniform emissivity. Measurements of the axial ratio of emission contours within a sample of normal spiral galaxies at 1500 MHz and below show no evidence for such a bright, extended radio halo. Either the Galaxy is atypical compared to nearby quiescent spirals or the bulk of the observed high-latitude emission does not originate from this type of extended halo.

Key words: Galaxy: halo – radio continuum: galaxies

auxiliary data:
thermal/non-thermal separation



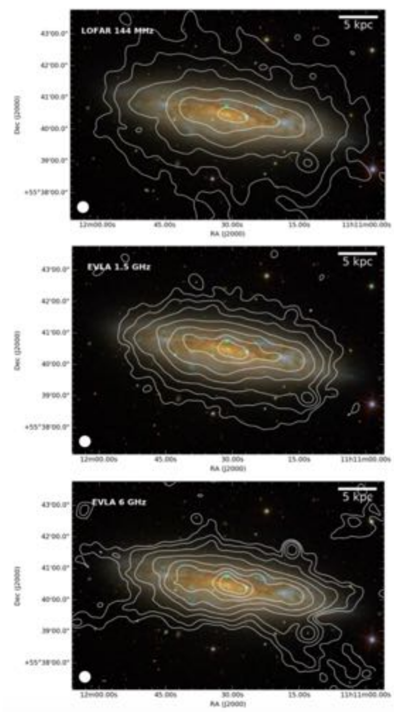
Dust corrected Hα image as thermal emission:

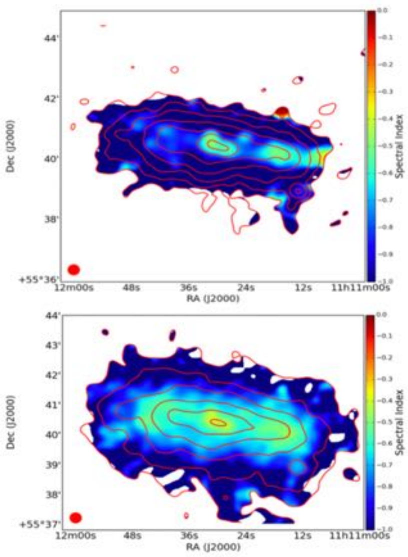
- WISE (22 μm) and Hα (in erg/s)
- Smoothing, regridding
- Calculating thermal Flux based on Calzetti et al. 2007

$F_{thermal} = C\ (L_{H\alpha} + 0.04\ L_{WISE})$

C. Vargas+ 2018. CHANG-ES X: Spatially Resolved Separation of Thermal Contribution from Radio Continuum Emission in Edge-on Galaxies

LOFAR/LoTTS + JVLA
CHANGES XII: N3556 (Miskolczi+ arXiv181104015)





spectral index much better described using a wind profile for v

$$v(z) = v_0\left(1 + \left(\frac{z}{h_v}\right)^{\beta}\right).$$

RUHR-UNIVERSITÄT BOCHUM

RUB

Summary:

- CRE transport seems to be dominated by advection in most star forming disk galaxies
- CR driven winds are likely to be important for the evolution of galaxies
- Halos of spiral galaxies have a significant poloidal magnetic field component (quadrupol field)
- New broad-band multichannel receivers provide higher sensitivity and allow for new analysis techniques such as Rotation Measure Synthesis
- LOFAR observations allow us to study the low energy and „old“ population of CREs
- Surveys aiming at measurements of magnetic fields and CRs in halos of a larger number of objects are underway

Supported by BMBF „Verbundforschung bodengebundene Astronomie und Astrophysik“

Thank you

NGC 46666 Credit: Y. Stein, J. Englisch, A. Miskolczi