Spiral galaxies
Radio properties (1)

- Radio emission: synchrotron, thermal bremsstrahlung

\[ S \propto \nu^{-\alpha} \]

- Spectral index distribution: \( <\alpha> \approx 0.74 \)

- Relative amount of thermal emission: median value 20%
Radio properties (2)

- Radio emission is a common phenomenon: $L_{1.4\text{GHz}} \sim 10^{18} - 10^{23}$ W/Hz

- Four components of the non-thermal radio emission:
  a) spiral arms
  b) disk
  c) nucleus
  d) halo

- Magnetic field (from equipartition) $\sim 8$ micro G (in the Milky Way $\sim 3$ microG)
Examples

Total intensity at 5GHz with a resolution ~ 15 arcsec superimposed onto the optical image

Linearly polarized intensity at 5GHz with a resolution ~ 15 arcsec superimposed onto the optical image, the vectors represent $\mathbf{B}$
Examples: barred galaxies

Intrinsic orientation of the magnetic field (regular and/or anisotropic random), obtained from polarized synchrotron emission, corrected for Faraday rotation and deprojected into the galaxies' planes, with the major axis oriented north-south.

The vector length is proportional to polarized intensity at 13.5 cm. The resolutions are 10 and 25 arcsec, respectively; the deprojected beam is shown in the lower right corner. Distances given in axis labels are in arcmin.

Beck+2005
a) Emission from spiral arms

Compression factor (arm/intra-arm) \(<~3\): depends on the difference in velocity between spiral structure (rigid body) and the matter; the velocity of the spiral structure \(\sim\) the velocity of the matter in the periphery.

Observations in agreement with the density wave theory: the spiral structure rotates more slowly than the matter \(\rightarrow\) shock waves in the internal part of the arm \(\rightarrow\) increase of the synchrotron emission.

- gas compression \(\rightarrow\) stellar formation \(\rightarrow\) stars need time to form \(\rightarrow\) the radio emission and the HII regions do not coincide (from the separation \(\rightarrow 10^7\) yr for the stellar formation).

In the unidimensional case:

\[
N_0 \propto \frac{l_0}{l} \propto \frac{\rho_0}{\rho} \quad H \propto \frac{l_0}{l} \propto \frac{\rho_0}{\rho}
\]

Synchrotron emissivity

\[
J = N_0 H^{1+\alpha}
\]

\[
\frac{J}{J_0} = \left(\frac{\rho}{\rho_0}\right)^{2+\alpha}
\]
a) Emission from spiral arms

For M51 the ratio of the computed emissivity is \( \sim 20 \), while the measured is \( \sim 3 \).

Probably, like in our Galaxy, the thermal gas is distributed in a region with width less than that of \( e \) and \( B \). Only in the region where \( e \) and \( B \) are mixed with thermal gas compression works

\( \rightarrow \) it is possible to compute the width considering the measured value of \( \sim 3 \)

\( \rightarrow \) the radio emitting matter has a width \( \sim 4 \times \) that of the thermal gas (\( \sim \) the same in our Galaxy)
b) Emission from the disk

- Radio emission decreases from the center (similar to the optical one)

- **Two components**: thermal and non-thermal (see M33 with radio data (3.6 and 20 cm) and Halpha data from which the thermal fraction was computed. For the whole galaxy 51% at 3.6 cm and 18% at 20 cm. Star forming regions are mainly spread over $R < 4$ kpc without dominant nuclear concentration).

Tabatabaei+2007, 2008
c) Central radio sources

- Many galaxies have a central compact region (<600pc) which contains ~20% of the total emission.
- No relation between the emission from the disk and the emission from the central source.
- The nature of the central source (BH or SF) can be determined from the spectral index and the variability (see M81).

X-ray data from the Chandra X-ray Observatory (blue), optical data from the HST(green), infrared data from the Spitzer Space Telescope (pink) and ultraviolet data from GALEX (purple).
d) Halo

- Halo is evident in external galaxies edge-on at low frequency
- At 85 MHz $J(\text{halo}) \sim 1/30 J(\text{disk})$
- $L(\text{halo}) \sim 1.5 \times 10^{38}$ erg/s

- Width ~ a few kpc (except NGC 891 ~ 6kpc and NGC 4631 ~ 12kpc)
- From the distribution of the brightness and the spectral indices → the distribution of $e$ in $z$
- X-ray halos associated with radio halos (Tullmann+ 2006)

NGC 3079 at 326 MHz, GMRT (at different resolutions)

NGC 3556 in the 0.3 -1.5 keV band (gray scale) and 20 cm continuum, Wang 2003
d) Halo

The halo luminosity in the radio range correlates with those in Hα and Xrays (Tüllmann et al. 2006), although the detailed halo shapes vary strongly between the different spectral ranges. These results suggest that star formation in the disk is the energy source for halo formation and the halo size is determined by the energy input from supernova explosions per surface area in the projected disk (Dahlem et al. 1995).

Almost edge-on spiral galaxy NGC253. Total radio intensity (contours) and B-vectors at 4.86 GHz, combined from observations with the VLA and the Effelsberg telescope (Heesen et al. 2009b)
Radio halos grow in size with decreasing observation frequency. The extent is limited by energy losses of the cosmic-ray electrons, i.e. synchrotron, inverse Compton and adiabatic losses (Heesen et al. 2009a). The stronger magnetic field in the central region causes stronger synchrotron loss, leading to the “dumbbell” shape of many radio halos. From the radio scale heights of NGC253 at three frequencies and the electron lifetimes (due to synchrotron, inverse Compton and adiabatic losses) an outflow bulk speed of about 300 km/s was measured.
d) Halo

High-sensitivity observations of several edge-on galaxies like NGC253, NGC891, NGC5775 (Tüllmann et al. 2000, Soida et al. 2011) and M104 (Krause et al. 2006) revealed vertical field components which increase with increasing height above and below the galactic plane and also with increasing radius, the so-called X-shaped halo fields. The field is probably transported from the disk into the halo by an outflow emerging from the disk.

Edge-on spiral galaxy NGC891. Total radio intensity (contours) and B-vectors at 8.35 GHz (3.6 cm), observed with the Effelsberg telescope (Krause 2009). The background optical image is from the CFHT.
Luminosity Function

- density of sources (per Mpc$^3$) with radio power between $(P, P+dP)$ or $(L, L+dL)$

- density of sources (per Mpc$^3$) with radio power $> P$ or $L$

To get direct $F(L)$ or $F(L)dL$:

- Identification
- redshift

Not easy, only 3CR complete id. and $z$

Both PLE and PDE rejected

Only brightest sources evolve (Longair, 1966)
Local Radio Luminosity Function

Local RLF derived from the 662 galaxies that are accepted as correct IDs and have radio flux density \( S > 2.8 \text{mJy} \) at 1.4 GHz, optical magnitude \( 14.0 < M_b < 19.4 \) and redshift \( 0.001 < z < 0.3 \).

\[
L_{\text{radio}} \propto L_{\text{opt}}
\]

Sadler+ 2002
**Local Radio Luminosity Function**

Two components:

- **Classical Radio-Loud AGN:**
  - knee at \( \log P \approx 24.5 \) (W/Hz)

- **Star Forming Galaxies:**
  - steep LF
  - \( \log P < 24.5 \) (W/Hz)
  - overcome AGNs at \( \log P < 23 \) (W/Hz)

Spirals have radio power
\( 10^{18} < P(1.4\text{GHz}) < 10^{24} \) W/Hz

90% have \( P < 10^{22} \) W/Hz
Composition of the ISM

- Globally $M(H_2)/M(HI)$ about 0.1-3 but in the centers of spiral galaxies $>10$.

- Relative amounts of HI and $H_2$ depend on galaxy morphological type (Casoli+1998, Bettoni+2003).

~90% H, ~9% He, <1% dust (metals)
HI

- Possible indicator of SF
- The HI mass depends on the morphological type:
  - \(<0.01\%\) in E and early type spirals
  - 5-10\% in late and intermediate spirals
  - Principal component in the blue galaxies
- Extension larger than the optical image
- Possible deficiency in the galaxy center
HI column density distribution (left) and velocity field (right) of NGC 864 and its companion, superimposed on the optical POSS2 red band image (espada+ 2005)

NGC 1511: interacting group. HI superimposed on the red image (Dahlem+ 2005)

$M_{HI} \sim 0.47 \times 10^9 \, M_{\odot}$

$M_{HI} \sim 4.3 \times 10^9 \, M_{\odot}$

$M_{HI} \sim 0.28 \times 10^9 \, M_{\odot}$
One of the major goals in studying spiral galaxies is to understand the relationship between the star formation process and the physical conditions in the interstellar medium.

Global studies have revealed relationships between the radio continuum (RC), far-infrared (FIR) and CO emissions. The global correlation between the FIR and centimeter-wavelength RC emission is one of the strongest correlations in extragalactic research.

Since the discovery that stars form in molecular clouds, several efforts have been directed towards the study of the relation between the emission of the CO molecule, which traces the bulk of molecular gas, and the other star formation indicators.
FIR/Radio correlation

SFGalaxies:

Remarkably tight correlation, spans over 5 orders of magnitude with a scatter of less than a factor of 2

\[ L_{1.4\text{GHz}} \propto L_{60\mu}^{0.99\pm0.01} \]

Recent massive star formation is the dominant process causing the correlation, but different radiative processes:

• thermal emission from warm dust around HII regions
• thermal emission from cool dust (the “cirrus”) associated with dust heated by the old stellar population
• Synchrotron emission
• Thermal free-free emission

Yun et al. 2002
Radio/FIR Correlation

Holds up to $z=1$

SDSS, Yun et al. 2002
Local Sample

$20 \log S_q S = \log \frac{S_{IR}}{S_{20}}$

Spitzer FLS, Appleton et al. 2004
Radio/FIR Correlation

The total radio and far-infrared (FIR) or mid-IR (MIR) intensities are highly correlated within galaxies. The exponent of the correlation is different in the spiral arms and the interarm regions (Dumas et al. 2011; Basu et al. 2012). The scale-dependent correlations between the radio synchrotron and IR emissions are strong at large spatial scales, but break down below a scale of a few 100 pc, which can be regarded as a measure of the electron diffusion length.
Correlation between the RC and CO emission in 22 galaxies (corrected for the galaxy inclinations).

Each point represents the average value within an annulus. The solid line is a weighted fit to the points shown, which takes into account the errors in both coordinates and has a slope of 1.1. In NGC 1068 is clearly present an AGN.
The correlation is observed over a large range of physical scales (from \( \sim 10 \) kpc to \( \sim 100 \) pc), but star formation is a local process.
Conventional model for Radio/FIR/CO correlation

- Massive stars with $M > 8M_{\odot}$
- Stars form
- Molecular clouds
- Hot stars
- Heating
- Warm dust
- FIR
- Radio continuum
- SN
- SNR
- ISM shocks
- Part. Accel.
- Transport
- Synchrotron
Star formation estimators
(Cram+ 1998, Hopkins+ 2001)

• **Halpha luminosity**: HII regions ionized by early-type stars

• **U-band luminosity**: substantial contribution from photospheres of young, massive stars

• **FIR power**: absorption of stellar photospheric radiation by grains, with subsequent re-radiation as thermal continuum

• **Radio continuum emission**: synchrotron radiation by relativistic electrons

\[
SFR_{H\alpha} (M \geq 5M_{\text{sol}}) = \frac{L(H\alpha)}{1.5 \cdot 10^{34} \text{W}} M_{\text{sol}} \text{ yr}^{-1}
\]

\[
SFR_{\text{FIR}} (M \geq 5M_{\text{sol}}) = \frac{L_{60\mu m}}{5.1 \cdot 10^{23} \text{WHz}^{-1}} M_{\text{sol}} \text{ yr}^{-1}
\]

\[
SFR_{U} (M \geq 5M_{\text{sol}}) = \frac{L_U}{1.5 \cdot 10^{22} \text{WHz}^{-1}} M_{\text{sol}} \text{ yr}^{-1}
\]

\[
SFR_{1.4} (M \geq 5M_{\text{sol}}) = \frac{L_{1.4}}{4.0 \cdot 10^{21} \text{WHz}^{-1}} M_{\text{sol}} \text{ yr}^{-1}
\]
SFR estimators

• **FIR/radio reflects the FIR/Radio correlation.** For SFR(1.4GHz)<0.2 M/yr high value of SFR(FIR), probably revealing some heating from interstellar field of older disk stars, without associated SN. Radio loud galaxies (high radio with respect to FIR).

• **Halpha/Radio more scattered.** For SFR<0.1M/yr a factor 10 above the trend (difficulty in zero-point level for Halpha emission; escape of cosmic rays from galaxies with weak SF→SF(radio) too low). For SFR>20 M/yr a factor of 10 below (due to extinction or to particular IMFs that favor low mass SN progenitors rather than high mass star responsible for Halpha)

• **U/Radio similar to the previous.** Flatter than FIR/Radio – even old stellar population emits U-band light.
Molecular gas in circumnuclear regions

Galactic nuclei characterized by high (stellar) mass concentration

- bulges, pseudobulges, stellar bars
- massive star clusters, nuclear disks, cusps, cores, ...

Molecular gas (not atomic) also tends to pile up in the central kpc of galactic nuclei

- nuclear gas disks, rings, bars and spirals

Why does the gas gravitate toward the circumnuclear regions?

- deeper gravitational potential
- tidal interactions and mergers rearrange gas and drive gas inflow
- secular evolution driven by bars and spiral structure density waves acting on disk material
Local deviations from exponential disk

On kpc circumnuclear spatial scales, there are deviations from the exponential stellar disk: rings, holes, spirals, bars, ... (see BIMA-SONG survey, Helfer+ 2001, 2003).
The NUGA survey at IRAM-Plateau de Bure


- 200 hrs observing time at PdBI, in ABCD configurations, over about 3 yrs (2001-2003). $^{12}$CO(1-0) 115.27 GHz, $^{12}$CO(2-1) 230.54 GHz

- Spatial resolution ~0.6” (at 230 GHz) – 2” (worst case 115 GHz). PdBI primary beam size 42” (115GHz), 21” (230GHz). Velocity resolution 10 km/s; continuum sensitivity ~ 2 mJy/beam (115 GHz), ~5 mJy/beam (230 GHz).

Diffuse molecular gas, $n<10^3$ cm$^{-3}$

Dense cloud cores, $n>10^4$ cm$^{-3}$

Largest angular size (LAS)

Subsequent 30-meter single dish (Pico Veleta) observations for short-spacing correction to recover diffuse flux possibly resolved out by interferometric observations: half-power beam size 22” (115 GHz), 12” (230 GHz)
NUGA CO images of galaxies (Papers I-XIV)

\[^{12}\text{CO}(1-0)\] \[^{13}\text{CO}(2-1)\]

(translated)

\text{LINER}

\text{LINER/SY 1}

\text{TRAN/LINER}

\text{SY 1}

\text{SY 2}

\text{HII/SY 1}

\text{TRAN/SY 2}

NUGA CO images of galaxies (Papers I-XIV)

CO follows dust extinction even on 100-200pc scales.
NGC 2782: contrasting spatial scales for HI, CO

HI plume on 50-60 kpc scales to northwest (Smith 1991)

Bulge-disk decomposition subtracted from 3.6 $\mu$m image (Hunt+ 2008) shows stellar bar, diameter $\sim$ 700pc
NGC 2782: contrasting spatial scales for HI, CO

HI plume on 50-60 kpc scales to northwest (Smith 1991)

Nuclear molecular bar aligns perfectly with stellar bar seen in 3.6 μm residuals (not easily visible without subtraction)
NUGA: The Seyfert 2 galaxy NGC 3147 (Casasola et al., 2008)

**CO(1-0)**

nuclear peak (AGN position) + 2 molecular rings or pseudo-rings (at r~1.8 kpc and r~3.6 kpc) in CO(1-0), which consist of individual GMC complexes with mass of a few $10^7 - 10^8 \, M_\odot$.

$M(H_2) = 3.8 \times 10^9 M_\odot$ (in agreement with Young et al 95)

Only the internal ring $M(H_2) = 2 \times 10^9 M_\odot$

---

NGC 2782 (Hunt et al. 2008)

NGC 6574 (Lindt-Krieg et al. 2008)
Results of the model and gas fueling in NGC3147
Casasola et al., 2008

The molecular gas is presently inflowing to the center (feeding rate ~0.5 $M_\odot$/yr), and probably feeding the low-luminosity Seyfert 2 observed in NGC 3147.

How to remove the angular momentum of the gas and to bring it to the centre to feed the AGN

The bar is contained inside the first CO ring.
**CO circumnuclear morphology: a mixed bag**

- H$_2$ masses in the inner kpc region range from: $3 - 5 \times 10^8$ to $>10^9$ Msun. The extraordinary case of NGC 1961 (Combes+ 2009) has $M(H_2) \approx 2 \times 10^{10}$ Msun.

- $M_{\text{dyn}} \sim RV^2/G$. $M(H_2)/M_{\text{dyn}}$ from a few percent up to $>20\%$. *This means that more than 1/5 of the mass in the central few kpc of a galaxy can be molecular gas!*

- There is *no unique morphology* associated with central regions of galaxies hosting low-luminosity active galactic nuclei (AGN). NUGA finds *gas rings, nuclear gas bars, nuclear spiral arms, disks, and lopsidedness*, which may or may not be associated with stellar features (or with gas inflow to the AGN).

- **CO generally follows the dust distribution**, but with some very local (scales $>300$ pc) variations... *Multiwavelength analysis important!***
Gas surface density correlated with star formation


Circumnuclear starbursts, ultraluminous infrared galaxies need only $H_2$ (CO).

Most normal spirals need $H_2+HI$ to bring them onto correlation!
Star formation and $H_2$

Gray points:
- individual data, pixel-by-pixel, from 23 galaxies
- 13” resolution, Nyquist sampled
- 30000 independent measurements

Red points:
- Median and scatter of binned data

(Leroy et al. 2008, 2009)

slope = 1.0 +/- 0.2
Star formation and \( HI \)

Gray points:
- individual data, pixel-by-pixel, from 23 galaxies
- 13” resolution, Nyquist sampled
- 30000 independent measurements

Red points:
- Median and scatter of binned data

(Leroy et al. 2008, 2009)

\( \text{HI} \) “saturates” at \( \sim 9-10 \text{ M}_\odot \text{ pc}^{-2} \) and is not correlated with \( \text{SFR} \).
Where do stars form?

Contours reflect data density of points averaged over ensemble of galaxies; equal weight to each radius (taken from Bigiel et al. 2008, Leroy et al. 2008, 2009).

- HI surface density saturates at ~ 9-10 Msun pc$^{-2}$
- Gas density correlates with SFR (slope = 1.0 +/- 0.2). Stars form where molecular gas is dense.
- Molecular gas KS law, but hot debate! (see Krumholz+ 2008, 2009 for theoretical motivation)
Molecular gas distribution in interacting galaxies

- CO morphology: Signature of interaction type and age - as well as evolutionary stage of the central activity.

NGC4194 - The Medusa merger
**CO/\(^{13}\text{CO}\) line ratio**

- **Global CO/\(^{13}\text{CO}\) J=1-0 line ratio increases** with increasing 60/100 mm flux ratio (e.g. Young and Sanders 1986, Aalto et al 1991, 1995)

- Elevated CO/\(^{13}\text{CO}\) J=1-0 line ratio caused by moderate optical depths:
  1. high kinetic temperatures, or
  2. presence of diffuse, unbound gas.

- Additional abundance effects in
  - outskirts of galaxies, low metallicity gas.
  - selective dissociation in PDRs (Photon Dominated Regions) in galaxy nuclei.

*Serves as tracer of large scale ISM structure and impact by dynamics and starformation*
Large scale ISM property gradients

a) Temperature gradients

- Temperature gradient in the molecular gas of the merger Arp299
  - Faint $^{13}$CO 1-0 in the nuclei of IC 694 and NGC 3690, but bright $^{13}$CO 2-1 emission.
  - High $^{13}$CO 2-1/1-0 line ratio expected when temperatures and densities are high
Large scale ISM property gradients

b) Diffuse molecular gas

- **Diffuse molecular gas** in dust-lane of the medusa merger.
  - Large-scale shift in CO and $^{13}$CO 1-0 peaks.
  - CO emission is tracing dust lane and nuclear starburst region
  - $^{13}$CO is not associated with dust lane but with the western side of the starburst.
  - $^{13}$CO peaks are one kpc away from CO peak.
AGN/SB

The thermal and chemical structures of the gas should significantly differ between SB- and AGN-dominated regions.

HCN/CO vs. HCN/HCO$^+$

(Kohno et al 2001)

Similar results for: $HCN, HCO^+, HCO^+ \rightarrow HCN$

Intensity ratios tend to be higher in the SB galaxies than in AGN galaxies, Krips+ 2008)
Chemistry as a diagnostic tool

ISM chemistry tracers are particularly important for the deeply obscured activity zones of luminous and ultraluminous galaxies.

- Assist in identifying dust enshrouded nuclear power sources: AGN or starburst
- Tracer of starburst evolution.
- Tracer of type of starburst? Are all starbursts alike - or do their properties vary with environment?
- Starburst-AGN connection.

Kohno et al.
HC$_3$N in LIRGs

• Surveys of LIRGs have revealed a handful of galaxies with luminous HC$_3$N 10-9 emission.
• Tracer of warm, dense, shielded gas. Quickly destroyed by UV photons and by reactions with C$^+$
• “Hot core molecule” – i.e. young star formation or very dusty, embedded AGNs?
• HC$_3$N luminous in LIRGs with deep IR silicate absorption (Costagliola et al 2008)
  - Correlation with IR excitation temperature (as derived by Lahuis et al 2007).
  - “Extended” hot core phase?
The dusty LIRG NGC 4418

- NGC 4418 is a dusty IR-luminous edge-on Sa galaxy with Seyfert-like mid-IR colours.
  - IR dominated by 80 pc nuclear structure of $T_B(\text{IR})=85$ K (Evans et al).
- What is driving the IR emission - starburst or AGN activity?
  - FIR-excess: young starburst?
  - No hard X-rays: starburst?
  - Broad NIR $H_2$ lines: AGN?
  - HCN/HCO$^+$ 1-0 line ratio > 1: AGN?
Rich Chemistry in NGC4418 - buried AGN or nascent starburst?

Bright HC$_3$N 10-9,16-15,25-24 detected. Ortho- $\text{H}_2\text{CO}$, CN, HCN, HCO$^+$, OCS (tentative). HNCO not detected.

All species - apart from HNC and HC$_3$N - are subthermally excited and can be fitted to densities $5\times10^4$ - $10^5$ cm$^{-3}$ (Aalto+2007).

HC$_3$N is vibrationally excited – governed by IR-field not collisions
52 3CR/B2 radio galaxies
28 detected in CO(1-0) and/or CO(1-2)
$M_{\text{mol}} \sim 4 \times 10^8 \, M_{\odot}$ (similar to Seyfert)
$T(\text{dust}) \sim 35.4 \, \text{K}$ (IRAS)
Molecular gas in elliptical radio galaxies (The B2 sample)

CO line detection \(\rightarrow\) dust in inner galaxy core \([<5-10 \, \text{kpc}]\)

Prandoni
Double-horn CO lines associated to rotating dusty disks

HST

0149+35

Mount Wilson

1122+39

Prandoni
**High-$z$ CO AGN** *(Omont 2008)*

In the list of Solomon & Vanden Bout (2005):

- 14 SMGs with $z=1.06-3.41$
- 16 QSO with $z=1.42-6.45$
- 5 Radio Galaxies with $z=2.39-5.20$

All the 11 objects with $z>3.5$ are prominent AGN:

- $\text{H}_2$ masses $\sim 10^{10} \, \text{Msol}$
- CO linewidths $\sim 200$-$800 \, \text{km/s}$ (QSO lower end, RG upper end)
- High fraction of interacting objects
The Impact of ALMA

• The interpretation of molecular lines towards obscured galactic nuclei: ALMA helps enormously through offering resolution and sensitivity. We can image ULIRGs with GMC-scale resolution.

• With existing telescope arrays, we are looking at ensembles of clouds -> Average properties of the molecular gas within the beam - but ALMA is changing all of this.
The measured spectrum of M82 as might be observed at different redshifts. Because of the K-correction effect, as the radiation grows fainter with distance, the peak of the radiation curves moves toward the red. In receiver bands 4, 6, and 7 of ALMA, we find that we continue to detect the galaxy with nearly equal sensitivity even as it recedes in distance.