The elaboration of spiral galaxies: morpho-kinematics analyses of their progenitors with IMAGES

by François Hammer
on behalf of the IMAGES collaboration


Intermediate Mass Galaxy Evolution Sequence
Galaxy Evolution since z=1

- CFRS, 1995-1997: strong decrease of star-formation density since z=1
- Half of present-day stellar mass density formed since z=1 (e.g., Dickinson+03; Drory+04)

*From evolution of:*
1. global stellar mass (photometry, near-IR)
2. integrated SFR (including IR light)

- Most of the stellar mass formed in LIRGs (SFR > 19 \( M_\odot/yr \))
- Mostly associated to evolution of interm. mass galaxies (Hammer+05, Bell+05):
  \[ 2 \times 10^{10} < M_{\text{stellar}} < 2 \times 10^{11} M_\odot, \text{ i.e. around Milky Way mass} \]
- Today, 70% of spirals…

*requires resolved kinematics of z~0.65 intermediate-mass galaxies*
Today: $z=0$

6 Gyrs ago: $z=0.65$

$M_J < -20.2$

$\sim M_{\text{stellar}} > 1.5 \times 10^{10} M_\odot$
**IMAGES-GTO Survey**

The deepest ever made observations of distant galaxies

**Sample selection**
- $M_J < -20.3$ & $0.4 < z < 0.9$
- 4 fields including CDFS

**Integrated properties**
- Spitzer
- VLT/FORS2 (600RI+600z)

**Imaging**
- ACS imagery

**3D Spectroscopy**
- VLT/FLAMES-GIRAFFE

**Intermediate-mass galaxies**
- $M_{\text{stellar}} > 1.5 \times 10^{10} M_\odot$
- (average $\sim M^*$, e.g. MW)

**SFR**
- Metallicity of the gas (O/H)

**Color-morphology**
- S.E.D.

**Kinematics**
- Dynamics
100 galaxies with spatially resolved kinematics

100 Intermediate mass galaxies:
- $M_J < -20.3$
- $0.4 < z < 0.9$

In this talk:

Representative sample of 63 Milky Way mass galaxies selected in 4 different fields of view, with $0.4 < z < 0.75$

From Yang et al (2008), A&A 474, 807
Velocity fields and also $\sigma$-maps

At low spatial resolution, dispersion maps of rotating disks do show a peak in their dynamical center.

$$\sigma_{\text{pixel}} = \sigma_{\text{random motions}} \otimes \Delta V_{\text{large scale motions}}$$

see e.g. Flores+06, Yang+08, Epinat+09
Resolved kinematics: rotating (Rot)

- ROT$_{HST}$

All distant galaxies are compared to local rotating disks:

- Large scale motions due to rotation
- Aligned with the optical axis
- Simulation of corresponding VF and $\sigma$-map
- Comparison of the derived $\sigma$-maps to the observed ones (relative difference of amplitude $\epsilon$ vs. $\sigma$ peak distance $\Delta r$)
Resolved kinematics: perturbed rotation (PR)

- $\text{ROT}_{\text{HST}}$
- $\sigma$
- $\text{S/N}$
- $\text{VF}$
- $\text{VF-model}$
- $\sigma-$model

- Rotation seen in the VF (aligned with the optical axis)
- Off-centred $\sigma$ peak

![Graph showing resolved kinematics and perturbed rotation](image)
Resolved kinematics: complex kinem. (CK)

- No obvious structure in the VF/σ-map;
- Dynamical axis generally misaligned vs main optical axis
Resolved Kinematics: statistics

- **ROT**
  - HST
  - VF
  - $\sigma$
  - S/N
  - VF-model
  - $\sigma$-model

- **PR**

- **CK**

Flores et al (2006)
Puech et al (2006a)
Yang et al (2008)

**Fraction of $z \sim 0.65$ intermediate-mass galaxies:**

- Normal rotation, ROT: 19%
- Anomalous kinematics: 41% (incl. PR: 15%, CK: 26%)
- Without emission lines (E/S0/Sa..): 40%
Morphology


Classification based on similarities with local galaxies
Semi-automatic decision tree: GALFIT + Colour maps + Visual inspection

Agreement between kinematics and morphological classifications

Morpho-kinematics

95% of CK are Peculiar, Compact or merger

80% of ROT are Sp
A small fraction of rotating spirals at $z=0.65$

Neichel et al, 2008

<table>
<thead>
<tr>
<th></th>
<th>with $\text{EW}([\text{OIII}])&lt;15\text{Å}$</th>
<th>with $\text{EW}([\text{OIII}])&gt;15\text{Å}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E/S0</td>
<td>23%</td>
<td>16%</td>
</tr>
<tr>
<td>RspD</td>
<td>17%</td>
<td>28%</td>
</tr>
</tbody>
</table>

33% of $z=0.65$ galaxies are rotating spirals against 70% today! It supersedes earlier results from Lilly et al (1998)

Based on:
Large scale kinematics (GIRAFFE)
+ detailed morphology HST/ACS 200pc @ $z=0.65$
## What evolve, what don’t

<table>
<thead>
<tr>
<th>Morphological Type</th>
<th>z ~ 0.65</th>
<th>z=0</th>
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</thead>
<tbody>
<tr>
<td>Neichel et al, 2008</td>
<td>23%</td>
<td>27%</td>
</tr>
<tr>
<td>Nakamura et al (04, SDSS)</td>
<td>33%</td>
<td>70%</td>
</tr>
<tr>
<td>E/S0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spiral</td>
<td>44%</td>
<td></td>
</tr>
<tr>
<td>Peculiar/compact/merger</td>
<td>Anomalous kinematics</td>
<td>~ 3%</td>
</tr>
<tr>
<td>LIRGs</td>
<td>20%</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

E/S0 mostly in place at z=0.65, half of spirals don’t evolve. Peculiar & LIRGs evolve by large factors: linked with spiral/disk formation.
The origin of star formation in progenitors of spirals 4-8 Gyrs ago

- Doubling their stellar masses
- Processes related to violent SF (LIRGs)
- At $z \sim 0.65$ half of local spirals were anomalous (kinematics & peculiar morphologies)
- They are responsible of the large scatter in the M-V (TF) (see poster by M. Puech)

Suggests galaxy collisions or their remnants
A giant, starburst, bar induced by a merger at $z=0.4$

A giant, starbust, bar induced by a merger at z=0.4


Galaxy morphology & angular momentum are driven by the last major merger (here 1:3 mass ratio, S0_a)
Half of the anomalous galaxies are obvious mergers


These are all before the fusion (two distinct nuclei) ==> ALL anomalous galaxies can be (and have been) reproduced by major mergers

Modelling morphology AND kinematics at z~ 0.65:

==> similar accuracy than for many local galaxies
A disk rebuilt 500 Myrs after a gas rich merger at $z \sim 0.4$


Barnes, 2002
Gas, INCLINED, 1:1
A disk rebuilt 500 Myrs after a gas rich merger at z~0.4

Hammer et al. 2009a

Observed gas fraction is 37% (from Kennicutt-Schmidt)
it was > 50% at the beginning of the interaction, 800Myrs ago

Spiral morphology & angular momentum are driven by the last major merger parameters:
here 1:1 mass ratio ==> Sc
Preliminary conclusions from IMAGES

Based on a representative sample of intermediate mass galaxies at $z \approx 0.65$

Half of local spirals had anomalous kinematics at $z \approx 0.65$

Detailed analyses reveal merger processes (more in progress)

Local disks rebuilt after a major merger?

Consistent with the spiral rebuilding scenario for which 50 to 75% of local disks might have been rebuilt following a major merger since $z=1$

(Hammer et al. 05; see also Hopkins et al. 08)
How disks form?

Angular momentum
 tidal torque theory « acquisition from early galaxy interactions »
(Eggen et al, 1962; Peebles, 1976; White, 1984)

⇒ Apply well to the Milky Way: no significant interactions since z~ 3

However:

- kinematics & morphology of distant galaxies
- angular momentum catastrophe
- Milky Way representativeness?
The Milky Way versus M31 and other spirals

Hammer+07

More accurate measurements of $M_K$, $R_{\text{disk}}$ (COBE, Spitzer) and $V_{\text{flat}}$ for the MW and M31

**Compared to other spirals (SDSS):**
- the MW has a too small stellar mass, radius & angular momentum;
- M31 is rather typical.

In the $(M_K, R_{\text{disk}}, V_{\text{flat}})$ volume, there are only $7\pm1\%$ of MW-like galaxies.

Star abundances in galactic outskirts (Fe/H, inner halo 5-30 kpc):
Most spirals (incl. M31) have stars in outskirts far more enriched than MW’s
(see also Mouhcine et al, 2006)
Conclusion

- the MW has an exceptionally quiet history since z=3: most other spirals (e.g. M31) may have had a much richer merger history;
- 6 Gyr ago half of the spiral progenitors were out of equilibrium, mostly showing merger remnant properties;
- Disk survival is a key issue! (Hammer+07; Stewart+08; Purcell+08, Hopkins+08)

Disk rebuilding scenario (Hammer+05) consistent with:
- distant galaxy properties (stellar mass assembly mainly through episodic IR phases driven by mergers);
- evolution of the gas content (31% at z ~ 0.65, Hammer+09)
- gas-rich progenitors able to rebuild significant disks (Lotz+08, Hopkins+08)

In excellent agreement with hierarchical prediction: both E & Sp are hierarchically formed

Potentially could solve the angular momentum catastrophe and explain the elaboration of the Hubble sequence
Few remarks

The redshift decrease of rotating spirals (factor 2 at $z \sim 0.6$) is consistent with the absence of convincing cases of massive rotating spirals at $z = 1.5-3$ (see e.g. Robertson & Bullock08).

The physics of disk building has to be fully revisited, possibly including:
- bar formation (see e.g. Hopkins+08);
- re-accreted gas & stars material (IMAGES project);
- ring formation?

==> a challenge for nearby galaxy studies:
- Could one find a nearby galaxy with Milky Way mass AND with either:

1. an anomalous morphology (irregular) & kinematics,
2. or anomalous star formation (doubling time $M_{\text{stell}}/\text{SFR} < 1 \text{ Gyrs}$),

THAT is not a major merger or a remnant?
Specific Angular Momentum

Puech et al. 2007, A&A 466, 83

\[ j_{\text{disk}} = 2R_d V_{\text{max}} \]

- A random-walk evolution of \( j_{\text{disk}} \)
- Dispersion of CKs consistent with major mergers

Using T.J. Cox simulations

\[ \text{Log } J_{\text{disk}} [\text{km} \cdot \text{s}^{-1} \cdot \text{kpc}] \]

\[ \text{Log } V_{\text{max}} [\text{km} \cdot \text{s}^{-1}] \]

- Complex Kinematics
- Perturbed Rotators
- Rotating Disks

Merger
\[ t = 1.8 \text{ Gyr} \]

Using T.J. Cox simulations
Galaxies with complex kinematics (CK): mostly major merger remnants?

Pair fraction at z~0.6: remarkable agreement on 5 ± 1 %
(Le Fevre+00; Conselice+03; Bell+06; Lotz+08; Rawat+08, Jogee+08)

Fraction of CKs at z~0.6: 26%
(Yang+08; see also Kudemir+08)

If CKs are major merger remnants, then:

\[
\frac{\tau_{\text{remnant}}}{\tau_{\text{pair}}} = \frac{f_{\text{remnants}}}{f_{\text{pairs}}} \approx 5
\]

Assuming \( \tau_{\text{pair}} = 0.3-0.5 \) Gyr \( \Rightarrow \) \( \tau_{\text{remnant}} = 1.5-2.5 \) Gyr

Predicted by simulations of major mergers
(e.g., Robertson+06; Cox+07, Governato+07)
Galaxies are not isolated systems

Rodrigues et al. 2008
arXiv:0810.0272
See Rodrigues poster

Comparison with TF evolution:

It needs that ~30% of the stellar mass must be formed from external gas supply

The closed-box model is ruled out
FLAMES/GIRAFFE on the VLT

8 to 24 hrs exposure on an 8 m

CFRS03.0488, z=0.46, (3''x2'')
IFU Mode: 15 x 3”x2” arrays
(20 sq. mlenses, 0”.52)

15 deployable IFUs over a 20 arcmin FoV with $R_{\text{effective}} = 13000$
⇒ the [OII] doublet is well resolved
A surviving disk from a 6:1 mass ratio central collision


Spiral morphology & angular momentum are driven by the last major merger parameters (here 1:6 mass ratio, Sa)
Learning from local spirals (including MW & M31)

Intermediate mass galaxies at z=0.6 are their progenitors, and many show anomalous kinematics due to merging

- MW past history \textbf{without} major interaction since z=3
- M31 \textbf{with} much more interactions


\textbf{Is MW a typical spiral or alternatively M31?}

\textbf{THE MILKY WAY, AN EXCEPTIONALLY QUIET GALAXY: IMPLICATIONS FOR THE FORMATION OF SPIRAL GALAXIES}

F. Hammer, M. Puech, L. Chemin, H. Flores, and M. D. Lehnert
Velocity fields and also $\sigma$-maps

Provided by: the absence of cross-talk between individual spectra.

$$\sigma_{\text{pixel}} = \sigma_{\text{random motions}} \otimes \Delta V_{\text{large_scale_motions}}$$

Blais-Ouellette, Amram et al, 2002

(Fabry-Perot/Halpha)

GIRAFFE pixel @ $z=0.6$
Galaxy Evolution since \( z=1 \)

- 50% of the local stellar mass was formed during the last 8 Gyr, i.e., since \( z=1 \) (e.g., Dickinson+03 ; Drory+04)

*From evolution of:*
1. global stellar mass (photometry, near-IR)
2. integrated SFR (including IR light)

- Mostly associated to evolution of interm. mass galaxies (Hammer+05, Bell+05) :
  - \( 2 \times 10^{10} < M_{\text{stellar}} < 2 \times 10^{11} M_\odot \);
  - Today, 70% of spirals;
  - Most of the stellar mass formed in LIRGs (SFR > 19 M_\odot/yr)

*requires resolved kinematics of \( z \sim 0.6 \) intermediate-mass galaxies*

Agreement between kinematics and morphological classifications

Automatic classification methods (C-A or Gini-M20):
• not predictive
• overestimate the number of spirals

only 16% of the sample is classified as Sp+RD

95% of CK are Peculiar, Compact or merger

80% of RD are Sp
A disk rebuilt 500 Myrs after a gas rich merger at z~0.4

Hammer et al. 2009a

- The kinematical axis is misaligned by 45° from the optical axis
- No outflows from spectroscopy ($z_{\text{abs}} \sim z_{\text{emi}}$ & NaD dominated by stars)
- The velocity dispersion peaks coincide with the end of the « two arms » system
- Half of stars have ages lower than 800Myrs
- Gas fraction is 37% (from Kennicutt-Schmidt) and was 67% 800Myrs ago
- All properties favour a merging scenario rather than a perturbed disk

Spiral morphology & angular momentum are driven by the last major merger parameters (here 1:1 mass ratio, Sc)
Gas ionisation induced by shocks in a z~0.6 forming galaxy


No stars but ionised gas

UDF

f_gas=73-82%

(SED fitting+TF & Kennicutt-Schmidt)

Barnes 02, DIR 1:1