Chemical Evolution and Star Formation History of the Disks of Spiral Galaxies in Local Group

Jun Yin (尹 君)

J.L. Hou, N. Prantzos, S. Boissier, R.X. Chang et al.

Shanghai Astronomical Observatory

11/18/2009

Content

Content

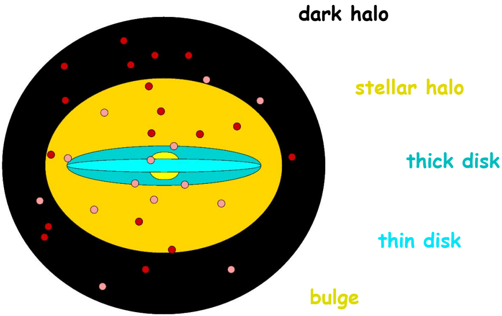
1. **Brief Introduction**
   - Basic Models
   - Basic Ingredients
   - Why Do This?
2. **MW vs. M31**
   - Comparison of Their Observational Properties
   - Models and Results
   - Discussions and Conclusions

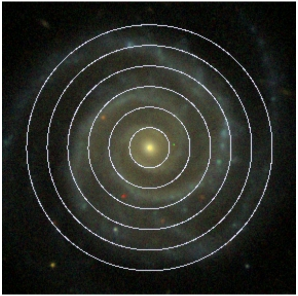
Content

Content

Brief Introduction on Chemical Evolution Models

General Picture

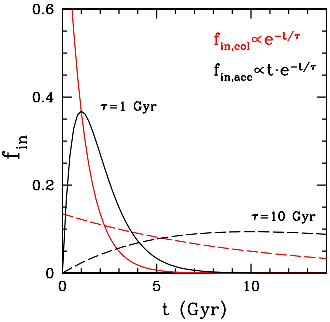




- Components: halo + thick disk + thin disk + bulge;
- Disks are built up by the infall of cooling primordial gas from their dark haloes;
- disk: exponential surface density profiles; concentric, independently evolving rings; no radial flow...

Basic Models

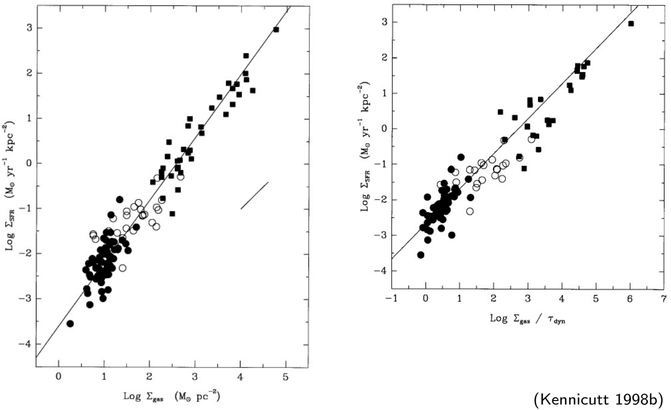
1. Close-box model
   - No exchange
2. Infall model
   - *collapse*: $f_{in,\ col} \propto e^{-t/\tau}$
   - *accretion*: $f_{in,\ acc} \propto t \cdot e^{-t/\tau}$ (peak at $t = \tau$)
   - Gaussian infall: $f_{in,\ gau} \propto e^{\frac{-(t-t_0)^2}{2\sigma^2}}$ (peak at $t = t_0$)
3. Outflow model
   - Outflow rate: $f_{out} = b \cdot \Psi(r, t)$



1. How many?
2. How born?
3. How evolve?
4. When die?
5. How die?

Star Formation Rate(SFR)

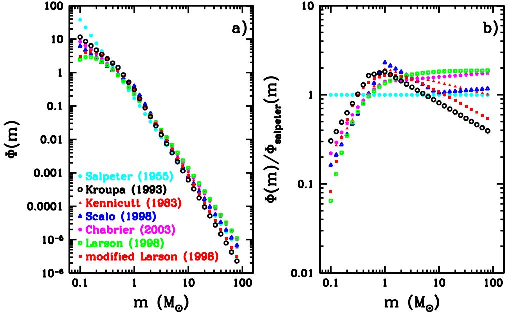
- Schmidt law: $\Psi \propto \rho_{gas}^{n}$ (Schmidt 1959,1963)
- K-S law: $\Psi \propto \Sigma_{gas}^{n}$ (Kennicutt 1998a,b)
- Modified K-S law: $\Psi \propto \Sigma_{gas}^{n}\, r^{-1}$ (Kennicutt 1998a,b)



(Kennicutt 1998b)

1. How many?
2. How born?
3. How evolve?
4. When die?
5. How die?

Initial Mass Function(IMF)



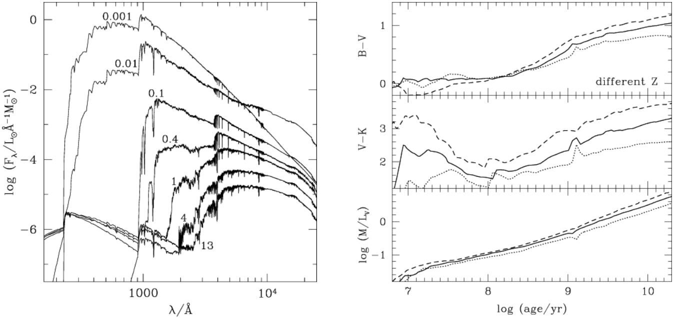
Kroupa IMF(1993, KTG93):

$$\Phi(m) = \begin{cases} 0.58\, m^{-1.3}, & (0.08 < m \leqslant 0.5) \\ 0.31\, m^{-2.2}, & (0.5 < m \leqslant 1) \\ 0.31\, m^{-2.7}, & (1 < m < \infty) \end{cases}$$

1. How many?
2. How born?
3. How evolve?
4. When die?
5. How die?

Theory of Stellar Evolution

- Stellar nucleosynthesis theory
- Stellar population synthesis theory



(Bruzual & Charlot 2003)

1. How many?
2. How born?
3. How evolve?
4. When die?
5. How die?

Mass-lifetime relation

Comparison between Larson(1974)and Rana(1991)

$m(M_\odot)$	0.1	0.5	1	2	8	30
$\tau_{m,Larson}$(Gyr)	3.09×10^5	1.50×10^2	10.5	1.06	3.39×10^{-2}	5.13×10^{-3}
$\tau_{m,Rana}$(Gyr)	7.10×10^4	5.95×10^2	27.0	1.67	3.48×10^{-2}	5.70×10^{-3}

1. How many?
2. How born?
3. How evolve?
4. When die?
5. How die?

Theory of Stellar Evolution (yield)

- Iron-peak elements:

  by SN Ia (intermediate-mass stars)

- $\alpha-$elements:

  by SN II (massive stars)

Why Do This?

- *Why* Spiral galaxies in LG?

  complement: Single vs. large sample; M31, M33 vs. MW;
  neighborhood: plenty of observations;

- *Why* phenomenological model of chemical evolution?

  simplicity: Complex processes are described by analytical laws;
  tool: observed present-day features, abundance, color...

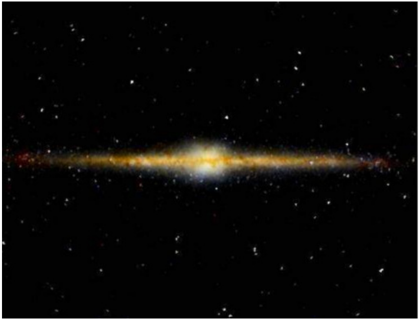
- Aims?

  Similarity and difference? Formation and evolution history? Unified framework?

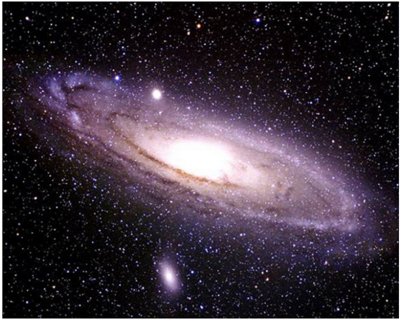
Chemical Evolution of Disks of MW and M31

(Yin et al., 2009, A&A)

Global pictures



Milky Way

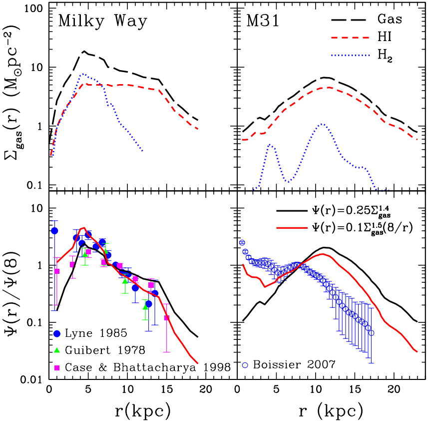


M31

Gas and SFR

Observation of MW and M31 Disks

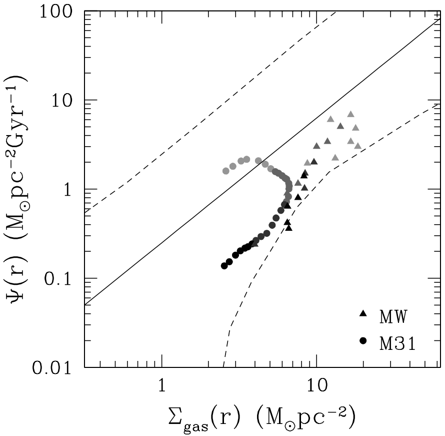
Observable	MW	M31
Total mass		
disk(10^{10} $M_\odot$)	3.5	∼7
star(10^{10} $M_\odot$)	3.0	∼6
gas(10^{10} $M_\odot$)	∼0.7	∼0.6
HI(10^{10} $M_\odot$)	0.4	∼0.5
H_2(10^{10} $M_\odot$)	0.11	$\sim 0.02 - 0.04$
Gas fraction	$\sim 0.15 - 0.2$	~ 0.09
Total SFR ($M_\odot$ yr^{-1})	$\sim 1 - 5$	$0.4 - 1.0$
Scale-length (kpc)		
U		7.7
B	$4.0 \sim 5.0$	6.6
V	$2.5 \sim 3.5$	6.0
R	2.3	5.9
I		5.7
K	$2.3 \sim 2.8$	4.8
L		6.08
this work	2.3	5.5



Gas and SFR

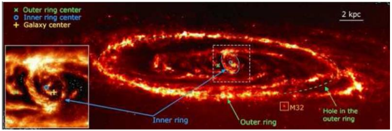
Observation of MW and M31 Disks

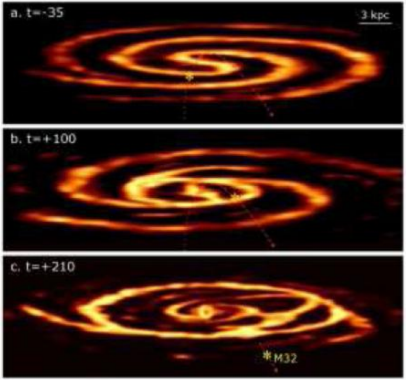
Observable	MW	M31
Total mass		
disk(10^{10} $M_\odot$)	3.5	∼7
star(10^{10} $M_\odot$)	3.0	∼6
gas(10^{10} $M_\odot$)	∼0.7	∼0.6
HI(10^{10} $M_\odot$)	0.4	∼0.5
H_2(10^{10} $M_\odot$)	0.11	$\sim 0.02 - 0.04$
Gas fraction	$\sim 0.15 - 0.2$	~ 0.09
Total SFR ($M_\odot$ yr^{-1})	$\sim 1 - 5$	$0.4 - 1.0$
Scale-length (kpc)		
U		7.7
B	$4.0 \sim 5.0$	6.6
V	$2.5 \sim 3.5$	6.0
R	2.3	5.9
I		5.7
K	$2.3 \sim 2.8$	4.8
L		6.08
this work	2.3	5.5



M31 may have experienced a major encounter with a nearby galaxy ∼200 Myr ago:

- Two-ring-like structures observed by Spizer (bottom);
- Numerical simulation (right).





(Block et al. 2006)

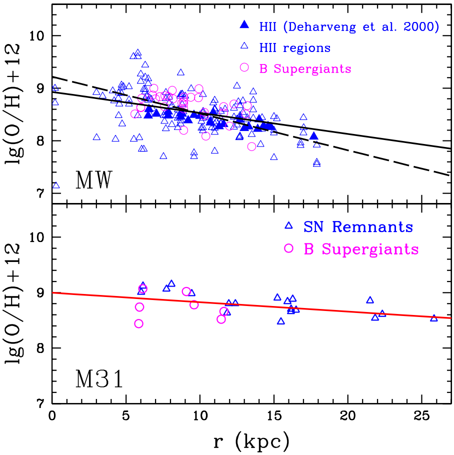
O abundance and gradient

- MW has steeper gradient:

  $-0.04 \sim -0.07$ dex/kpc

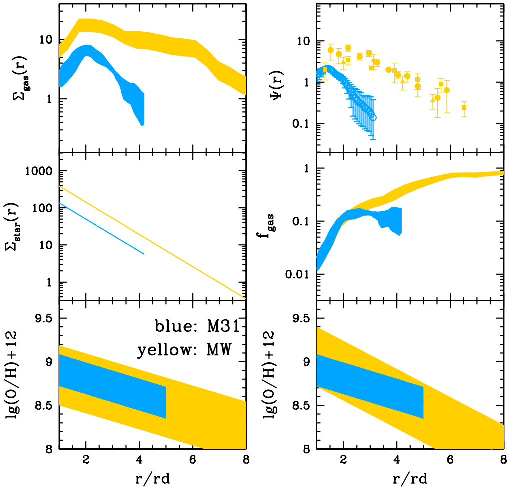
- M31 has flatter gradient:

  -0.017 dex/kpc



A unified description of MW and M31

- $r_{d,MW} = 2.3$ kpc, $r_{d,M31} = 5.5$ kpc



Former works

1. Plenty of observations on GC, halo, and outer disk;
2. SFH of outer disk or halo;
3. Few works on modeling disk, and the observational constraints used are limited:
   1. SFR$\propto$ $\mathrm{e}^{-t/\tau}$: 5-11 kpc, produce G-dwarf problem(Diaz 1984)
   2. SFR$\propto$ Σ_{gas}: biased infall; more gas in inner disk(Josey & Arimoto 1992)
   3. SFR$\propto$ Σ_{gas}^2/R: more gas in outer disk (Renda et al. 2005)

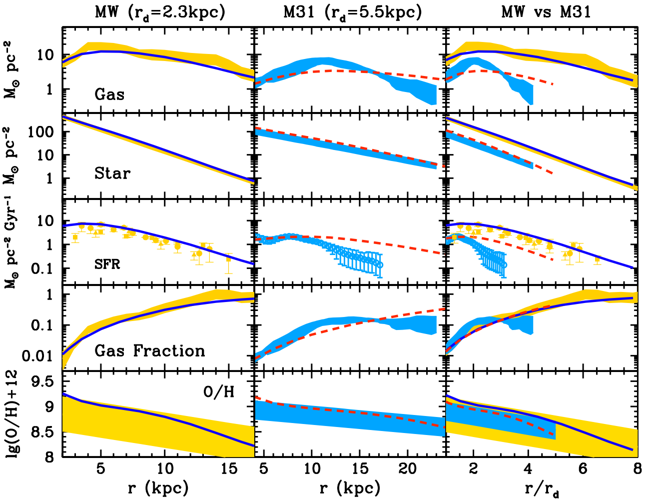
The Models in our work

Model parameters of disks of MW and M31

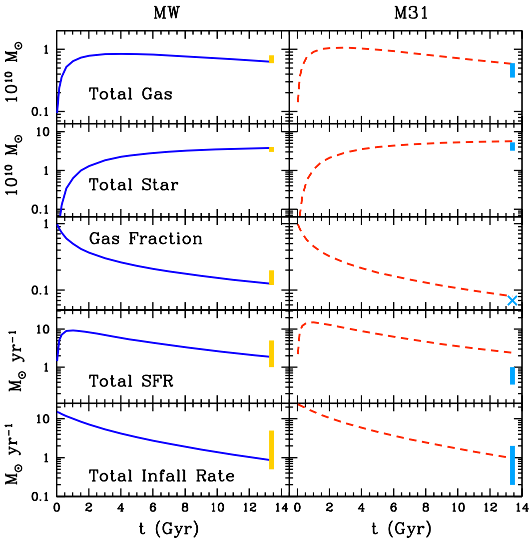
Individal	Milky Way	M31
Scale-length r_d (kpc)	2.3	5.5
Equivalent $r_{eq\odot}$ (kpc)	8.0	19.0
Total disk mass (10^{10} $M_\odot$)	5.0	7.0
V$_c$ (km s^{-1})	220	226
General	Prescription	Free parameters
Age of disk (Gyr)	13.5	
IMF	KTG93	
Mass limits	$(0.1 - 100)$ $M_\odot$	
Stellar yields	vdHG97, WW95	
Infall rate ($M_\odot$ pc^{-2} Gyr^{-1})	$f(t,r) = A(r)\ e^{-t/\tau(r)}$	
Metallicity of infall gas	$Z_f = 0$	
Infall timescale (Gyr)	$\tau(r) = k\ (r/r_d)$	$k = 2.5$
SFR ($M_\odot$ pc^{-2} Gyr^{-1})	$\epsilon\ \Sigma_{gas}^{1.5}(r/r_{eq\odot})^{-1}$	$\epsilon_{MW} = 0.1,\ \epsilon_{M31} = 0.2$

Radial profiles

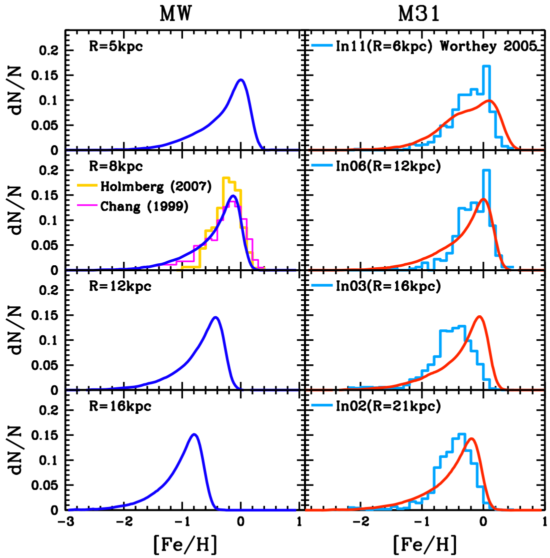
1. Gas
   broad peak, $\sim 2r_d$
2. Star
   exponential disk
3. SFR
   MW: fit well;
   M31: higher in outer disk, perturbations
4. Gas fraction
   increase outwards;
   similar on scale of r_d
5. O abundance gradient
   similar on scale of r_d



Time evolution of global properties



Metallicity distribution function (MDF)



Discussions

1. Renda et al. (2005) have done similar research:
   - Similarity: 'inside-out', M31 needs higher ϵ, predict higher gas and SFR in outer disk;
   - Difference: two-phase model, SFR$\propto \Sigma_{gas}^2/R$, higher gas profile;
   - Can't compare further: they do not provide SFR and stellar or gas fraction profiles.
2. MW is quiescent, M31 is more typical?(Hammer et al. 2007, Mouhcine et al. 2005);
3. Such simple models are more suitable for quiescent disks, like MW.

Conclusions

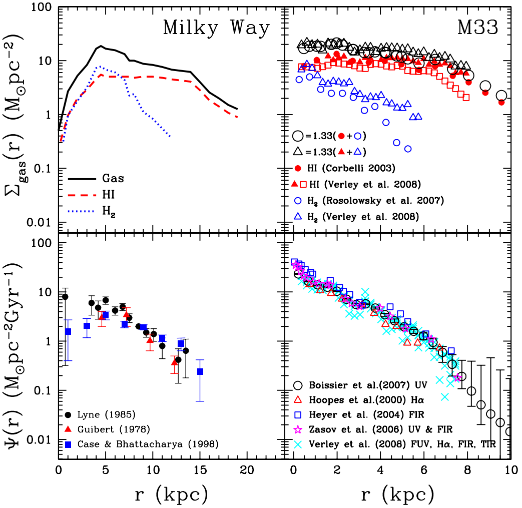
1. Summarized and compared the observational data for MW & M31: show lots of similarities when expressed in term of r_d;
2. Most radial profiles and global properties can be well described by our simple unified model, provided $\epsilon_{M31} = 2 \cdot \epsilon_{MW}$;
3. Produce high SFR in the outer disk and globally, attribute this to perturbations;
4. Reproduce MDF well.

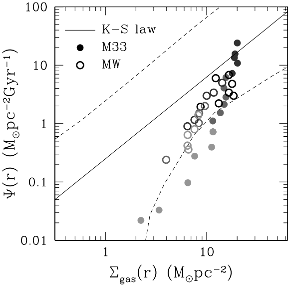
Chemical and Color-Evolution of M33 Disk

Global picture

- Sc II-III, $i = 54°$, D=840 kpc
- $M_{tot} = 5 \sim 8 \times 10^9\ M_\odot$
- $r_{d,tot} = 2.2 \sim 2.4$ kpc,
  $r_{d,*} = 1.4 \sim 1.5$ kpc
- No merging or interaction

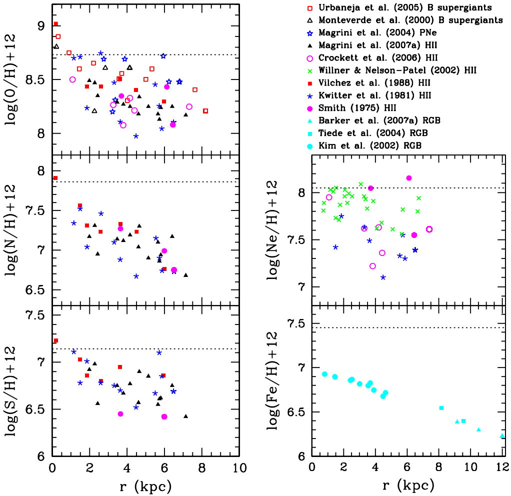
Gas and SFR profiles





- $M_{H_2} = 0.2 \times 10^9\ M_\odot$
  $M_{HI} = 2.2 \times 10^9\ M_\odot$
- r_{d,H_2}=2.5 kpc
  $r_{d,gas}$=7.8 kpc
- total SFR: 0.2-0.7$M_\odot$yr^{-1}

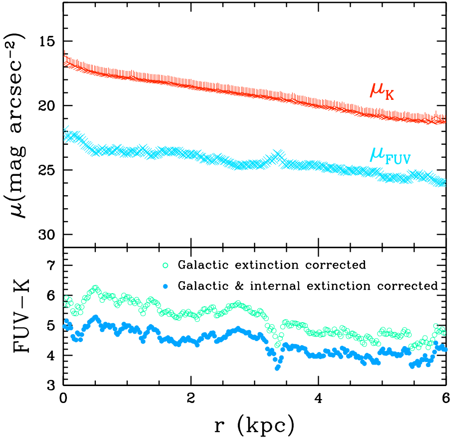
Metallicity and gradients



Observations of O gradient

Objects	radius (kpc)	Oxygen (dex kpc^{-1})
HII,	1.0–5.7	−0.13
optical	0.2–6.5	−0.070±0.008
	0.4–6.5	−0.127±0.011
	0.3–11.0	−0.19±0.03
	0.7–7.3	−0.012±0.011
	0.7–7.3	−0.054±0.011
	0.7–3.0	−0.19±0.08
	3.0–7.3	−0.038±0.015
	0.2–6.2	−0.027±0.012
B stars	0.2–4.1	−0.16±0.06

Surface brightness and color profiles



(Muñoz-Mateos et al. 2007)

Former works

- Barker & Sarajedini (2008)
  1. Main constraint: color-magnitude diagram($r \sim 9$ kpc);
  2. Discussed different infall histories;
  3. Main conclutions: $>$50% gas inflow takes place in the last 7 Gyr and $<$10% within the last 3 Gyr.
- Magrini et al. (2007)
  1. Main constraints: gas surface density profile, abundance gradients;
  2. Discussed abundance and gradients of different elements;
  3. Main conclutions: *accretion* model is better than *collapse* one, continuous infall and SF.

Models

1. Mass distribution
   - $M_{tot}(t_g) = 7 \times 10^9\ M_\odot,\ r_{d,tot} = 2.2$ kpc
   - $\Sigma_{tot}(r, t_g) \propto\ e^{-r/r_{d,tot}}$
2. Infall and outflow
   - Infall rate: $f_{in,acc}(r,t) = A_{acc}(r) \cdot t \cdot \mathrm{e}^{-t/\tau(\mathbf{r})}$
   - Infall delay time: $t_d(r) = \mathbf{a} \cdot r$
   - Outflow rate: $f_{out}(r,t) = \mathbf{b} \cdot \Psi(r,t)$
3. SFR
   - $\Psi(r,t) = \epsilon \cdot \Sigma_{gas}^{1.4}(r,t) \left(\frac{r}{r_{d,tot}}\right)^{-1}$

Does M33 form quickly?

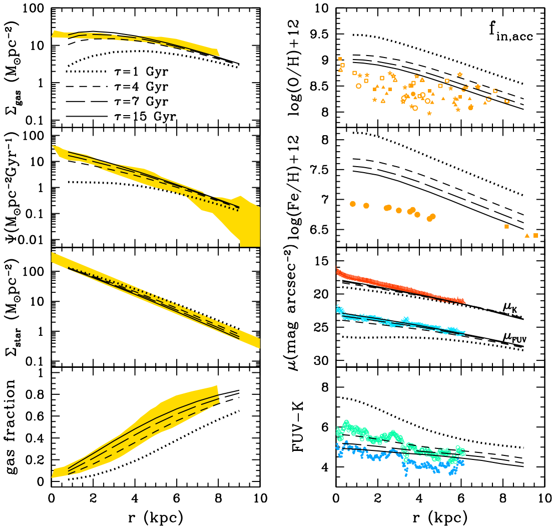
infall	τ	t_d	b	ϵ
$f_{in,acc}$	1,4,7,15	0	0	0.14

$\tau \Downarrow \Rightarrow$ infall faster

1. present gas, SFR density $\Downarrow$
2. present stellar density $\Uparrow$
3. gas fraction $\Downarrow$
4. abundance $\Uparrow$, steeper
5. SB $\Downarrow$, color redder, steeper

Conclusions

1. NO, τ should be longer, slow accretion process;
2. Problems: high Z, steep gradient, dark SB



Does whole disk form simultaneously?

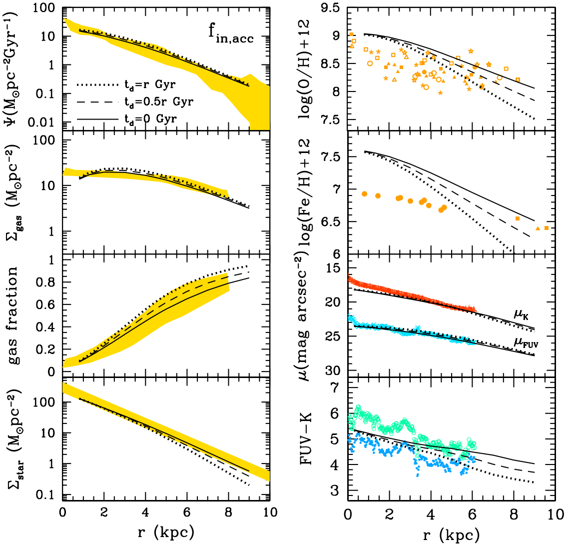
infall	τ	t_d	b	ϵ
$f_{in,acc}$	$r+5$	$r, 0.5r, 0$	0	0.14

$t_d \Uparrow \Rightarrow$ infall begins later

1. evolution time shorter;
2. gas fraction $\Uparrow$;
3. present stellar density $\Downarrow$;
4. evolution inadequate, abundance $\Downarrow$, steeper;
5. FUV slightly brighter, K slightly darker;
6. color bluer, steeper;

Conclusions

1. Not necessary
2. Problem: high Z, steep gradient

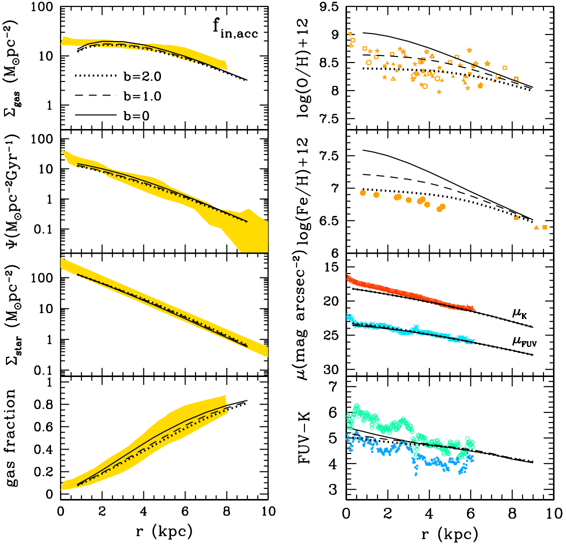


Does gas flow out?

infall	τ	t_d	b	ϵ
$f_{in,acc}$	$r+5$	0	2.0,1.0,0	0.14

$b \Uparrow \Rightarrow$ more outflow

1. more gas infall
2. gas, SFR, star change little
3. abundance $\Downarrow$, gradient flatter
4. SB, color change little



Conclusions

1. YES!
2. outflow rate $\sim$ SFR

Best model

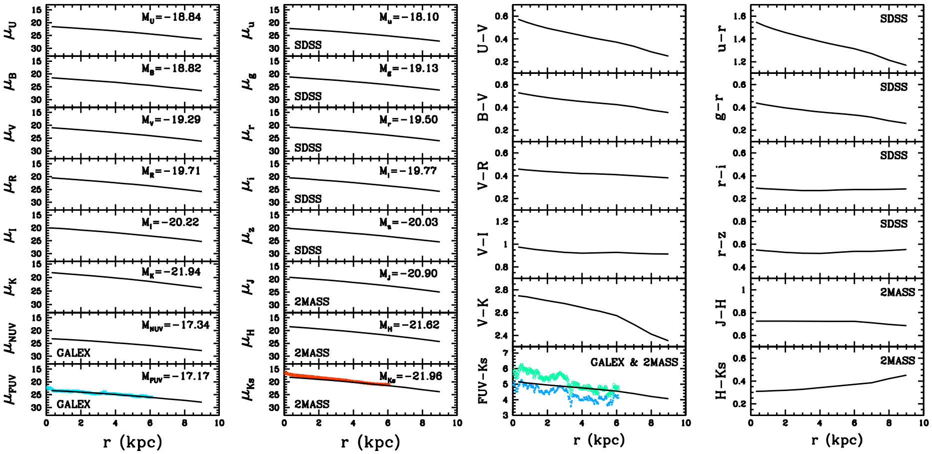
Best model of M33 disk

Basic parameters	
Age of disk (Gyr)	13.5
Total mass (10^9 $M_\odot$)	7.0
Scale-length of total disk $r_{d,tot}$ (kpc)	2.2
IMF	KTG93
mass limits	$(0.1 - 100)\ M_\odot$
Stellar yields	vdHG97, WW95
SFR ($M_\odot$ pc^{-2} Gyr^{-1})	$\Psi(r) = 0.14\Sigma_{gas}^{1.4}(r/r_{d,tot})^{-1}$
Infall rate ($M_\odot$ pc^{-2} Gyr^{-1})	$f_{in,acc} \propto t{\cdot}\mathrm{e}^{-t/\tau(r)}$
Metallicity of infall gas	$Z_f = 0$
Free parameters	
Infall time-scale (Gyr)	$\tau(r) = r + 5$
Infall delay time (Gyr)	$t_d = 0$
Outflow rate ($M_\odot$ pc^{-2} Gyr^{-1})	$f_{out}(r) = \Psi(r)$

Best model

Surface Brightness of 16 bands

12 color profiles



Conclusions

1. The disk of M33 should be formed by continuous accretion of gas (long infall time-scale) and whole disk should form simultaneously, consistent with former works;
2. Through the study of abundance, Outflow should play an important role in the evolution history of M33; Garnett(2002): Galaxies with $V_{rot} \lesssim 125$ km s^{-1} may lose a large fraction of their supernova ejecta; $V_{rot,M33} \approx 110$ km s^{-1};
3. Color gradients predicted by our model are flatter. Considering the uncertainty of extinction correction, our results are acceptable.

Summary and Work in Future

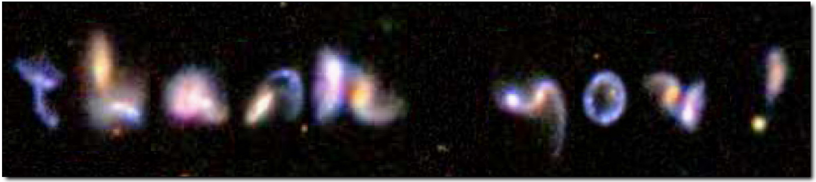
Summary

Discussed the evolution and formation history of 3 local spirals in details.

1. Similarities: common framework, infall + modified K-S law
2. Differences: MW and M31: massive, earlier infall, no outflow;
   M33: less massive, infall late, outflow takes place.
3. Intrinsic reasons: Mass? surface density? size? Angular momentum?

Future Works

1. Color-evolution of MW and M31;
2. Include more ingredients: halo+disk, disk+bulge, et al.;
3. Within cosmological framework;
4. Apply to other nearby spiral galaxies;
5. Include interaction;
6. ……


thank you!