HST/ACS photometry of M51 disk: Measurement of pattern speed

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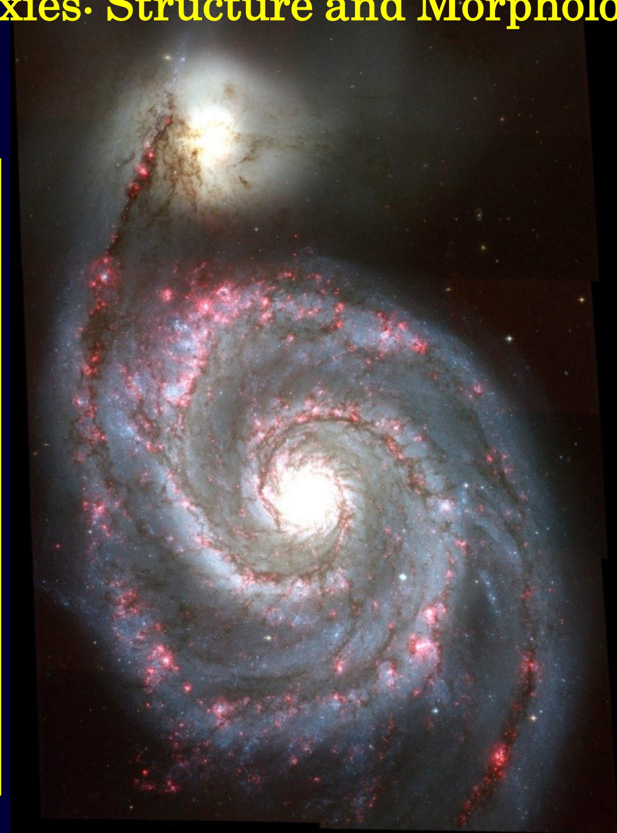
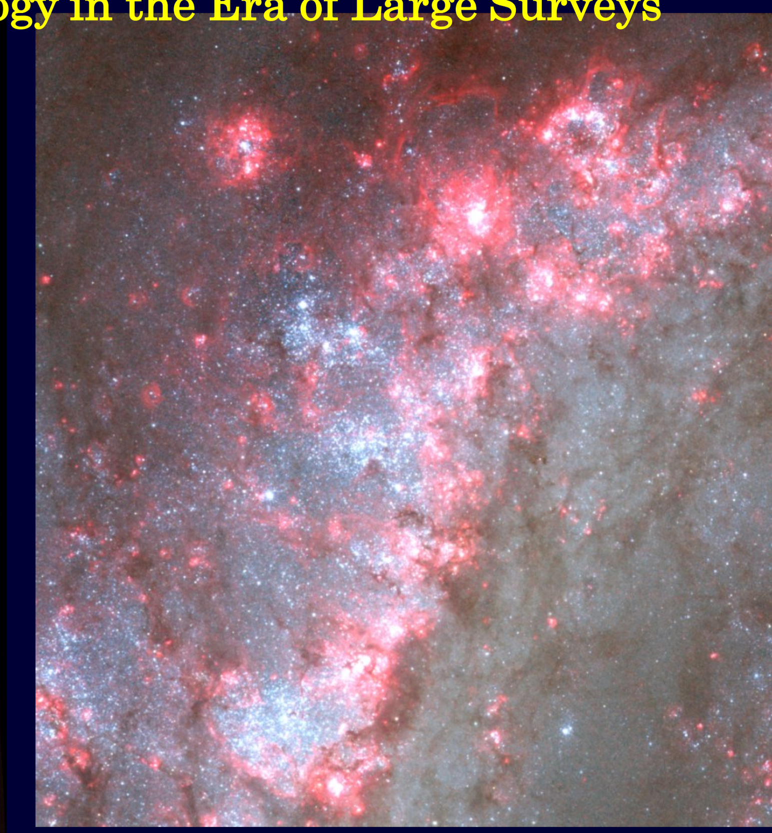
Deconstructing Galaxies: Structure and Morphology in the Era of Large Surveys

We report the HST/ACS photometry of M51/N5195. Two important deductions are as follows: 1) By applying offset method, the corotation radius is 5 kpc, which is essentially consistent with past determinations. However, the two main arms are both bending when CO gas and OB stars are concerned, inferring that the assumption in the offset method, i.e. long-standing wave and/or constancy of time for star formation might be inappropriate. 2) Red stars are resolved into young red-supergiants and older red-giant branch stars. They are mapped separately for the first time and we found that red-supergiants contribute at least by 20% in luminosity in the star-forming regions, indicating that simple surface brightness distribution in red do not necessarily indicate the distribution of old stars and thus of the gravitational potential.





Data

- NASA/HST Heritage program (ID 10452, PI: S.V.W. Beckwith)
- Images: obtained on Jan/2005(15th anniversary of HST); archived on Apr/2005
- FITS distribution: High-Level Science Product via MAST/STScI) (Mutchler+ 05)
- Area: 6 ACS/WFC mosaic on M51+ NGC5195 (covers most of R_{25} region)
- Size: 430"×610": 8600pix×12200pix, 350MB each
- Pixel scale: 0.05 arcsec (corresponding to 2.3pc at M51, assuming 9.6Mpc)
- Bands: F435W(B), F555W(V), F814W(I), F658N($H\alpha$), with a FWHM of 0.1"
- Exposure : 4 exposures for each mosaic tile
- Limiting magnitude (Vega): B = 26.5(2720s), V = 26.0(1360s), I = 25.3(1360s)
  - ✓ threshold are 4.0σ & 6.4σ for V and I-band, respectively; to suppress fake detections. Almost no compromise in detection.
- Due to the crowdedness, the smaller the fitting radius, the smaller is the reported error.
- Confusion limit in the SFRs; a shallower detection by no more than 0.3 mag
- Catalog contains 271465 V&I detected objects, with position, magnitude, shape parameters
  - ✓ Measured with DAOPHOT and Sextractor, the latter is useful for classification of objects (Fig. 1).
- Send request of the catalog to: hasegawa@astron.pref.gunma.jp

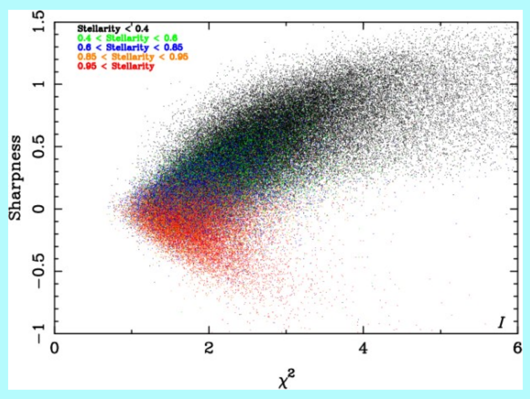


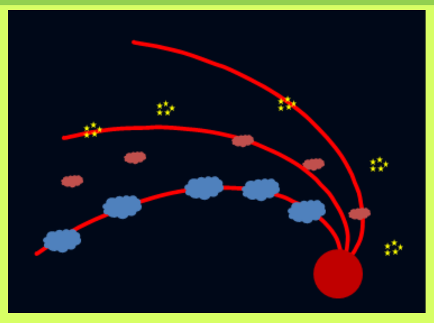
Fig. 1

How did this work begin…

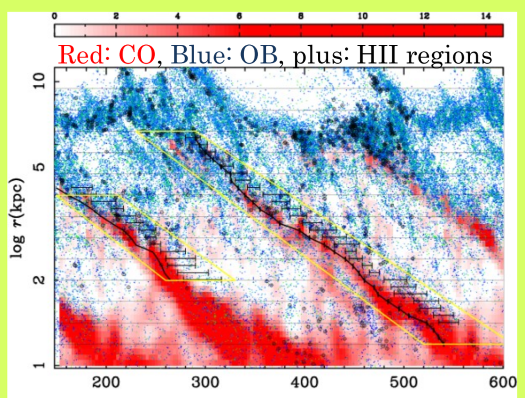
- We dealt with KS star-formation law in the open school this winter; We re-appreciated the superb resolving power of HST/ACS M51 images. However, very limited past investigations are found:
  - ✓Scheepmaker+ (2007): detection of 1284 clusters
  - ✓Kaleida & Scowen (2010): 120 young clusters (eye-inspection)
  - ✓Lee+ (2011): star-formation history with pixel analysis
  - ✓Lee+ (2011), Gutierrez+ (2011): List of Hα emitting regions

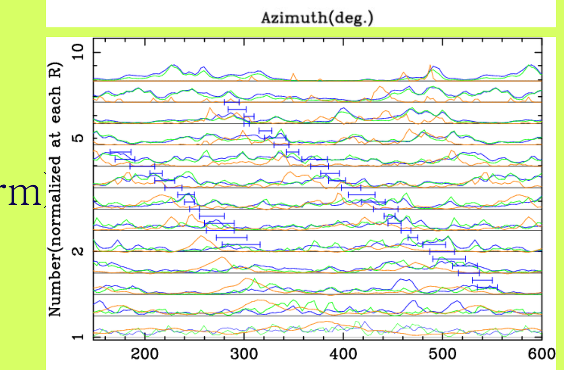
Measurement of Pattern speed

- Offset method (e.g. Egusa+ 04,09; Louie+ 2013)
  - ✓ separation : $d(\mathrm{HII}-\mathrm{CO}) = [V(r) - V_p] \times t_{SF}$ (t_{SF}: time for star-formation)
  - ✓ angular offset : $\theta(\mathrm{HII}-\mathrm{CO}) = [\Omega(r) - \Omega_p] \times t_{SF}$
  - ✓ ASSUMPTIONS: We expect a linear regression (Fig. 2), if:
    - Ω_p is constant (long-standing arm of the density wave (DW) theory)
    - t_{SF} is constant
- Choice of the tracer (Louie+ , 2013)
  - ✓ Location of gas compression: HI, CO
  - ✓ Location of star-formation: Hα emission; 24μm emission
  - ✓ Louis+ (2013) concluded that CO(Gas) and Hα(SFR) are the best.
  - ✓ We use OB stars (SFR) for the first time : independent reliable measure of time(upper limit), ample in number (but, still the largest error source).
- Pattern speed & Corotation radius (Fig. 3)
  - ✓ Ω_p ~ 40km/s/kpc; $r_{corotation}$ ~ 5 kpc
    - ✓2nd arm is not used beyond 4 kpc (strong pull of N5195 would deform the arm
  - ✓ Consistent with past results (Egusa+ 09); consistent with the structure that no strong gas emission and no prominent arm beyond this radius
- Diagnostics of the disk
  - ✓ Obviously *nonlinear* $\Omega - \theta$ relation; Strong dip at 2~3 kpc in two main arms
  - ✓ Constancy of t_{SF} and/or DW theory may be inappropriate (Wada+ 2011). The observed relation is consistent with the fast pattern speed in the inner disk, as often found in the radial dependence of pattern speed from the TW method. If the disk has TWO distinct zones, what is the mechanism ?



Schematic view of the offset method





Azimuthal profile of OB/RSG stars

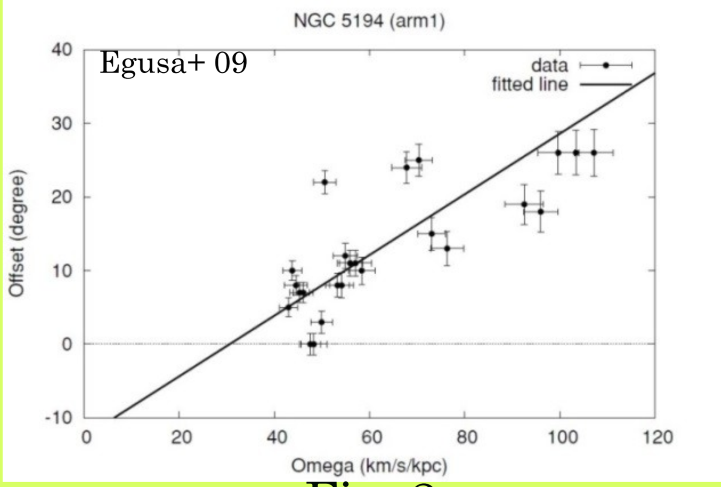


Fig. 2

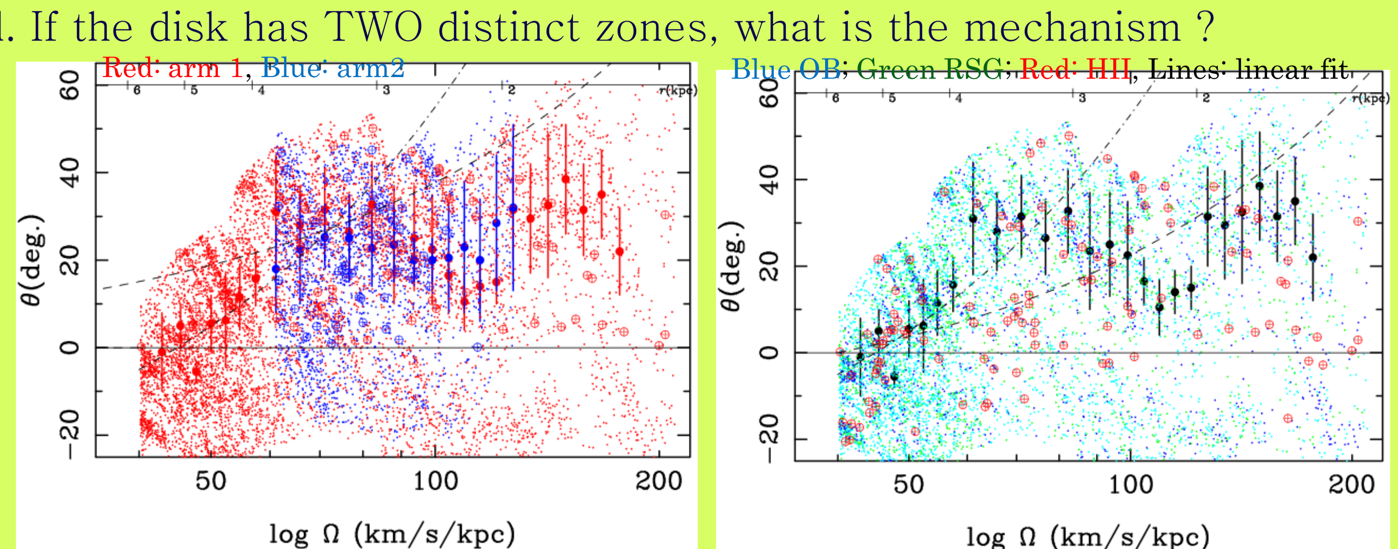
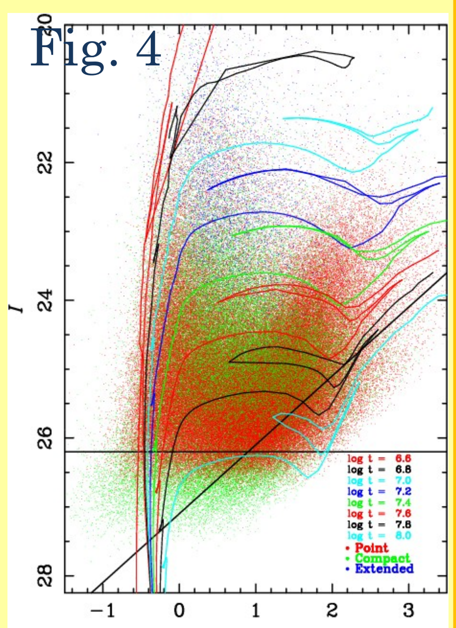


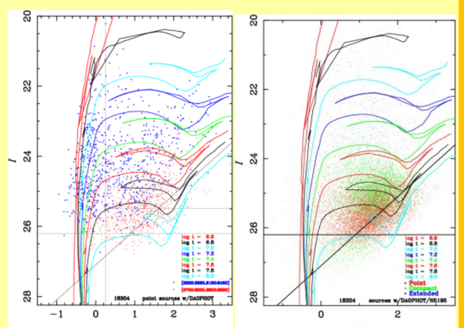
Fig. 3

Archaeology

- We superposed isochrones (Girardi+ 2002), with $m-M$ = 29.91 (9.6 Mpc), and A_V = 0.12, A_I = 0.07 (Fig.4).
  - ✓ MSTO: log t(Gyr)<7.6
  - ✓ RGB: log t(Gyr) < 7.8
  - ✓ $V-I$ ~0.5 & I < 24 are star clusters etc.
- SFRs are rich in red-supergiants (RSG). The distribution of RSG ($V-I$ > 1.0 & I < 24.5) traces SFRs (Fig. 5), and RSG contribute by 15% at least in I-band (this is a significant underestimate, Fig. 6). Surface brightness even in red bands may still suffer from RSG and not stand for old stars that follow the gravitational potential.
- The distribution of RGB stars shows a density contrast of ~3 between arm and interarm region (Fig. 6). Deeper photometry is necessary to finalize this important factor.

Fig. 4





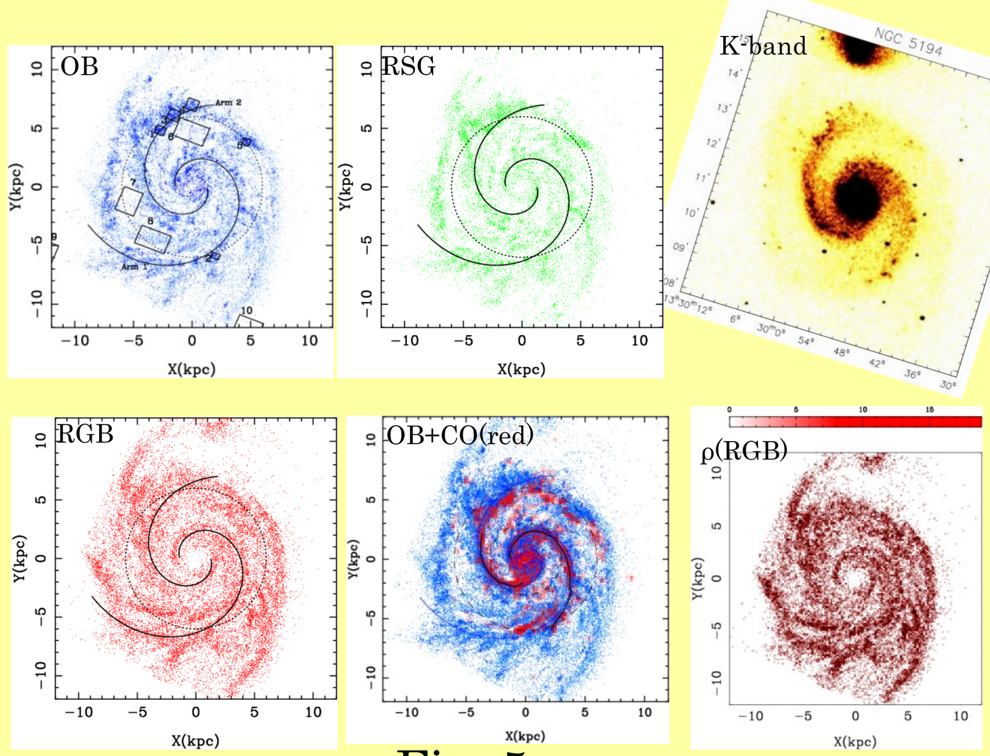


Fig. 5

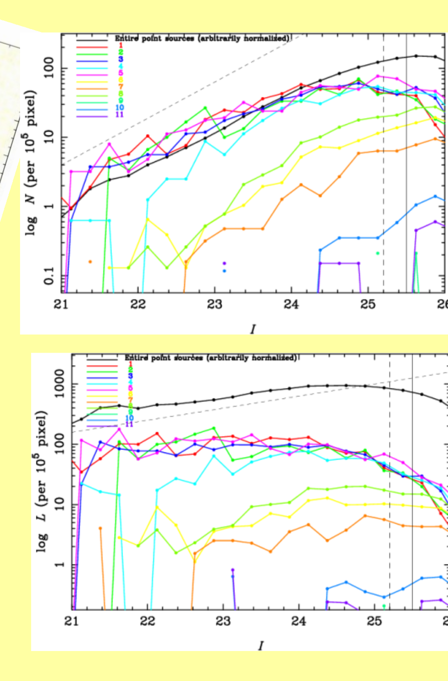


Fig. 6

Future Work

- Apply TW method for radial dependence of pattern speed.
- Hα business: dependence of stromgren radius on location.
- Hα business: Classification of Hα emitting objects…

Conclusion

- A photometric catalog of M51 and NGC 5195 is constructed based on HST/ACS/WFC heritage observation.
- It is found that pattern speed is ~ 40 km/s/kpc and corotation radius ~ 5 kpc; confirming the results from HII regions. However, $\Omega - \theta$ relation is non-linear and therefore constancy of star-formation time-scale and/or density wave theory (long-standing arm) may not be the case.
- Red-supergiant stars are rich in the star-forming regions, enough to contribute more than 20% in the I-band luminosity.