‘Eppur si muove’

Kinematic Studies of Galaxy Assembly Across Cosmic Time

$z > 1$ vs $z = 0$

Karl Glazebrook
Vesto Slipher
Sep 17th 1912 – first redshift

LOWELL OBSERVATORY

BULLETIN No. 58

THE RADIAL VELOCITY OF THE ANDROMEDA NEBULA

Keeler, by his splendid researches on the nebulae, showed, among other things, that the nebulae are generally spiral in form, and that such nebulae exist in far vaster numbers than had been supposed. These facts seem to suggest that the nebulae were probably the original of the universe, and the生产和 development of the universe. When making this exposure the brightness of the nebula on the slit-plate compared with that of the clusters indicated that one night’s exposure should suffice for the single-prism, and suggested that, by extending the exposure through several nights, one could employ the battery of

This result suggests that the nebula, in its swift flight through space, might have encountered a dark “star,” thus giving rise to the peculiar nova that appeared near the nucleus of the nebula in 1885.

The one obstacle in the way of the success of this undertaking is the faintness of these nebulae. The extreme feebleness of their dispersed light is difficult to realize by one not experienced in such observing, and it no doubt appears strange that the magnificent Andromeda Spiral, which under a transparent sky is so evident to the naked eye, should be so faint spectrographically. The contest is with the low intrinsic brightness of the nebular surface. a condition which no choice of telescope can relieve. However, the proper choice with the spectrograph will make the best of this difficulty. The collimator must of course fit the telescope, but the dispersion-piece and the camera may and should be carefully selected for their special fitness for the work. While the speed of the observing program with the 24-inch telescope did not allow an opportunity to carry out the original plan to make the longer exposure spectrogram with the prism-train.

These spectrograms were measured with the Hartmann spectrocomparator, using a magnification of fifteen diameters. A similar plate of Saturn was employed as a standard. The observations were as follows:

1912, September 17, Velocity, —284 km.
November 15–16, “ 296
December 3–4, “ 308
December 29–30–31, “ —301

Mean velocity, —300 km.

Tests for determining the degree of accuracy of such
able and fully confirms those of a year ago. The inclination of the lines which is analogous to that produced by the diurnal rotation of a planet, is unmistakable and leads one directly to the conclusion that the nebula is rotating about an axis. Although from the time of Laplace it has been thought that nebulae rotate, this actual observation of the rotation is almost as unexpected as was the discovery that they possessed enormously high radial velocities.

Karl Glazebrook, S.J.

The slit of the spectrograph was placed over the nebula rotate, this actual observation of the rotation is almost as unexpected as was the discovery that they possessed enormously high radial velocities. The fact that this nebula has a radial velocity of fully a thousand kilometers per second, as established here a year ago, makes it not so surprising that it should also be rotating rapidly.

and it has shown exceptional efficiency. Its power for the detection of rotation may be better understood when it is pointed out that it gives half as much inclination to the spectral lines as would the powerful three-prism spectrographs as used in velocity work with the great Lick and Yerkes refractors and yet requires less than one-seventy-fifth as much exposure as they would need for such nebulae. In the light of present
On September 17, 1912, Vesto Slipher obtained the first radial velocity of a “spiral nebula” — the Andromeda Galaxy. Using the 24” telescope at Lowell Observatory, he followed up with more Doppler shifts, and wrote a series of papers establishing that large velocities, usually in recession, are a general property of the spiral nebulae. Those early redshifts were recognized as remarkable by Slipher, and were critical to the discovery of what came eventually to be called the expanding Universe. Surprisingly, Slipher’s role in the story remains almost unknown to much of the astronomical community.

The nature, and especially the distance, of spiral nebulae was fiercely argued — most famously in the 1920 Shapley–Curtis debate. Hubble’s 1923 discovery of Cepheids in Andromeda, along with Henrietta Leavitt’s period-luminosity relation for Cepheids, led to a distance scale for the nebulae, enabling Lemaître (1927) to derive a linear relation between velocity and distance (including a “Hubble constant” and, by 1931, a Primeval Atom theory).

Meanwhile, a new concept of space and time was formulated by Einstein, providing a new language in which to understand the large-scale Universe. By 1932, all the major actors had arrived on stage, and Universal expansion — the most general property of the Universe yet found — acquired a solid basis in observation and in the (relativistic) concept of space. “Space expands”... or does it? How did Lemaître and Hubble interpret this concept? How do we interpret it? It continues to evolve today, with cosmic inflation and dark energy presenting new challenges still not fully assimilated.

This 100th anniversary conference will bring together astronomers and historians of science to explore the beginnings and trajectories of the subject, at the place where it began.

www.lowell.edu/workshops/slipher
This talk

- Star forming disks at $z \sim 0$ and $z > 1$ are quite phometrically and kinematically different

- $z > 1$: the observational evidence for giant CLUMPS in DISKS and physics setting mass scale

- Good evidence for (rare) local analogs, ‘cosmic fossils’ – can be studied in detail and so may allow fundamental questions about early star-formation to be answered
What is a disk, kinematically?

Line of Sight Velocity

(Distribution of Dark Matter in...)

(Albada et al. 1985)
Tully-Fisher relation

Bell & De Jong (2001)

Mo, Mao & White 1998:

\[ M_d = \frac{m_d V_c^3}{10GH(z)} \]
Cosmic Star-formation History

\[ \rho_*, (M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}) \]

\[ \log(1+z) \]

Hopkins & Beacom 06

Karl Glazebrook, SUT

Wednesday, 18 July 12
Star Forming Massive Galaxies $1.3 < z < 2.0$

(Gemini Deep Deep Survey HST montage: Abraham et al. 2007)
Integral Field Spectroscopy
Laser Guide Star Adaptive Optics

Palomar LGS–AO First Light
June 13, 2006

Seeing–limited
FWHM = 1.02"

LGS–AO
FWHM = 0.16"
Figure 17. Velocity fields for 30 of the 62 galaxies of the SINS H$\alpha$ sample. The velocity fields correspond to that derived from the H$\alpha$ line emission as described in Section 5.1 (the exception is K20–ID5 for which it was obtained from the [O\textsc{iii}]$\lambda$5007 line instead). The color coding is such that blue to red colors correspond to the blueshifted to redshifted line emission with respect to the systemic velocity. The minimum and maximum relative velocities are labeled for each galaxy (in km s$^{-1}$).

All sources are shown on the same angular scale; the white bars correspond to 1$''$, or about 8 kpc at z = 2. The galaxies are approximately sorted from left to right according to whether their kinematics are rotation-dominated or dispersion-dominated, and from top to bottom according to whether they are disk-like or merger-like as quantified by our kinemetry (Shapiro et al. 2008). Galaxies observed with the aid of adaptive optics (both at the 50 and 125 mas pixel$^{-1}$ scales) are indicated by the yellow rounded rectangles.

(A color version of this figure is available in the online journal.)

For the more compact objects or for data sets with lower $S/N$, kinemetry is too uncertain or impossible. In those cases, we sorted the galaxies based on a qualitative assessment of the asymmetry in the velocity field and dispersion map (essentially, the same criteria as for our quantitative kinemetry). We find in this way similar fractions of $\sim 2/3$ of objects that appear to have H$\alpha$ kinematics consistent with rotation in a single disk, and $\sim 1/3$ with asymmetric or irregular H$\alpha$ kinematics suggestive of a merger. We note that for the 15 objects classified quantitatively, our kinemetry confirmed in all cases our prior qualitative assessment (see Förster Schreiber et al. 2006a; Genzel et al. 2006, 2008; Shapiro et al. 2008). As noted in Section 2, the SINS H$\alpha$ sample includes three pairs of galaxies at approximately the same redshift and with projected separations of $\approx 15–30$ kpc. The individual components can in principle be counted and inspected separately (see Section 9.4) or take as three merging systems, but this has little consequences on our overall classification.

Another important characteristic of galaxies is the amount of dynamical support provided by rotational/orbital motions and by turbulent/random motions. Ideally, the distinction between "rotation-dominated" and "dispersion-dominated" kinematics would rely on detailed and accurate dynamical modeling, from Förster Schreiber et al. (2009) SINS survey K-selected/high stellar mass UV-selected/lower stellar mass merger Förster Schreiber et al. (2009) SINS survey Wednesday, 18 July 12
TFR at $z=2$?

Cresci et al. (2009) – SINS survey

Karl Glazebrook, SUT

Wednesday, 18 July 12
Line-of-sight velocity dispersions

**$z \sim 0$**

Andersen et al. 2008

DISKMASS survey

$\sigma / v_{\text{circ}} \sim 0.1$

**$z \sim 2$**

Genzel et al. (2011)

$\sigma / v_{\text{circ}} \sim 0.5$
$z \sim 0$

Stellar thin disk $\sigma_z \sim 20$ km/s, $h_z \sim 200–300$ pc

Stellar thick disk $\sigma_z \sim 40$ km/s, $h_z \sim 1500$ pc

HI gas, molecular gas, GMCs, HII regions, OB stars

$\sigma_z \sim 5$ km/s, $h_z \sim 50$ pc

(Note thermal $10^4$K broadening of H$\alpha = 9$ km/s)
HI gas, molecular gas, sGMCs?, sgHII regions (~1–2 kpc), OBA stars
$\sigma_z \sim 50$ km/s, $h_z \sim 1500$ pc
Why? The ‘turbulent clumpy disk’ scenario
Unstable Toomre Disks
(Elmegreen 2009)

\[ Q_{\text{gas}} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{\text{gas}}} \]

\[ \Rightarrow \left( \frac{\sigma_0}{v_c} \right) \left( \frac{a}{f_{\text{gas}}} \right) \]

\[ Q \sim 1 \Rightarrow f_{\text{gas}} \sim \sigma/v \sim 0.5 \]

\[ M_{\text{Jeans}} \sim \frac{\sigma^4}{G^2 \Sigma_g} \sim 10^8 - 10^9 M_\odot \]

c.f. $< 10^6 M_\odot$ at $z = 0$
Evolution of giant star-forming clumps

Gas richness $\rightarrow$ velocity turbulence $\rightarrow$ giant star clusters?

Elmegreen & Bournard (2008)
Gas richness?

Figure 3. High molecular gas fractions in star forming galaxies at high-z. a) The distribution of molecular gas fractions, for all 23 SFGs with good stellar mass estimates from $z \sim 1-3.5$. b) A comparison of the distribution of molecular gas fractions for the $z \sim 1$ (red) and $z \sim 2$ (blue) SFGs from this study. We define $f_{\text{mol-gas}}(CO) = M_{\text{gas}} / (M_* + M_{\text{gas}})$. The molecular gas mass and fractions include a correction of 1.36 for helium.

Tacconi et al. (2012)

$t_{\text{gas}} \sim \frac{10^{10} \, M_\odot}{100 \, M_\odot \, \text{yr}^{-1}} = 0.1 \, \text{Gyr}$
Cold Streams

Dekel et al. (2009) (see also Keres et al., van der Voort et al.)
Origin of thick disks?

Chain galaxies were first recognized by Cowie et al. (1995) using the same definition as that here. Tadpole galaxies were defined by van den Bergh et al. (1996), and examples from the UDF were discussed by Straughn et al. (2004). Tadpole galaxies with short tails were classified as ’’comma’’ type in the morphology review by van den Bergh (2002). Van den Bergh et al. (1996) also noted objects like clump clusters and called them ’’protospirals.’’ Conselice et al. (2004) called these clump-dominated young disk galaxies ’’luminous diffuse objects,’’ although some of their sample included galaxies with bulges and exponential-like profiles, unlike the clump clusters here. Binary galaxies, like our doubles,
Key Questions

• What drives the high velocity dispersions in Hα?
  (traces cold ISM? What sustains the turbulence?)
• Connection to high-star formation rates?
  Simply gas richness?
• Connection to galaxy (clumpy) morphologies?
• Are there local analogues?
• What is the ‘star formation law’ (gas→stars)
  Does the Kennicutt Schmidt law hold?
z>1 clumps

The morphology-kinematics connection?

+ Karl Glazebrook, Chris Blake, Greg Poole, (SUT), Andy Green (AAO), Ted Wyder, Chris Martin (CIT) & WiggleZ team,

Emily Wisnioski (SUT→MPE)
z~1.3 high SFR WiggleZ galaxies

(bolometric UV properties match z~2)

H\ α AO intensity images

WiggleZ Kinematic Sample

disk disk no rotation?

(Wisnioski et al. 2012)
1) Clumps trace global rotation

(Genzel et al. 2011)

(Wisnioski et al. 2012)
2) Clumps trace Toomre instability

\[ Q_{\text{gas}} = \frac{\sigma_0 \kappa}{\pi G \Sigma_{\text{gas}}} \]

Cheat! \[ \Sigma_{SFR} \]

(Wisnioski et al. 2012)

(Genzel et al. 2011)
3) Clump SFRs trace Jean’s mass

(Wisnioski et al. 2012)
4) Clumps drive superwinds

(Wisnioski et al. 2012)  (Genzel et al. 2011)
Local (z~0.1) Analogs of turbulent disks?

**DYNAMO team:** Karl Glazebrook (P.I.), Lee Spitler, Greg Poole (SUT), Emily Wisnioski (MPE), Peter McGregor, Rob Sharp, Matthew Satterthwaite (ANU), Roberto Abraham (Toronto), Ivana Damjanov (Harvard/CfA), Pat McCarthy (Carnegie), Matthew Colless, Rob Sharp (AAO), Erin Mentuch (Arizona), Danail Obreschkow (ICRAR), Rob Crain (Leiden)

Thanks to the **SPIRAL** and **WiFES** IFS instruments!

Andy Green (AAO)
High H\(\alpha\) SDSS galaxies?

Star Formation Rate (\(M_\odot/yr\))

- This Study, \(z \sim 0.1\)
- \(z \sim 0.01\) (refs 18,19)
- \(z \sim 1.4\) (ref 4)
- \(z \sim 2.3\) (ref 7)
- \(z \sim 3.5\) (ref 8)

\(H\alpha\) Luminosity (log erg/s)

\(\phi(\log L_{H\alpha}) [\text{Mpc}^{-3}\text{dex}^{-1}]\)

- \(z \sim 0.1\) ‘disk’
- \(z \sim 0.1\) ‘non-disk’

Green et al. (Nature 2010)
1) Really turbulent disks?
The arctangent function means that this value is of absolute magnitude Tully Fisher Relation (TFR), which compares the circular velocity with the absolute parent magnitude from the SDSS pipeline to an absolute magnitude in a given band. We convert the circular velocity measured at – exponential disk scale length – to a typical circular velocity in the middle of the disk for a self-gravitating exponential disk, which would be a peak. Although the Tully Fisher Relation has been expressed in many different forms, particularly when the velocity is still increasing at the largest observed radius, we choose to focus on three: the traditional circular velocity-TFR, which is the largest observed velocity, and two others that are intermediate between this and the systems observed at the apogalactic scale lengths.

The scatter is reduced when stellar mass and kinetic energy due to non-circular motions are included. Systematic errors will be largest for objects with complex kinematics and smallest for rotating disks. Points are coded by their position on the galaxy disk, with rotation vectors indicated by the dashed line in Panel B, which shows the stellar mass TFR. Panel C shows the kinetic classification as in the key in Panel B. No points have been excluded from this plot, even though not all are rotating.

These relationships are inferred at the disk scale lengths from disk fitting. Points are coded by their galaxy classification as in the key, and a single circular velocity must be assigned to each galaxy. Although the TFR can be summarized in Figure 8, Weiner's rule – absolute magnitude Tully Fisher Relation (TFR) – does not apply to our sample in a variety of different environments. The TFR and the TFR with stellar mass are shown by the solid lines, with the relations of Pizagno & Green et al. 2012 shown by the dashed lines. Green et al. 2012 (in prep.) shows the relation in the y – Green et al.
2) Are they clumpy?
Pa-α with Keck AO resolution! (0.1 arcsec = 200 pc)
3) Are they gas rich?

Don’t know – ALMA time please!
**Dust properties?**

**Herschel! (GO Program)**

- Local SDSS Galaxies
- AGN (This Study)
- IRGs (D00)
- SMGs (C05, K06)
- ULIRGs (Y07, Y09)
- $z=1.3$ Disks/LBGs (WiggleZ)

**Arp 220**

**MW**

**CLIRG?**

**HlumAz_9-1: $z=0.18$**

- SFR=75 Msolar/yr

**High-z SMGs**

Wednesday, 18 July 12
4) Are the *stars* in a turbulent disk?

Testing *stellar kinematics* using Gemini/GMOS IFU
Prediction: velocity dispersion of stellar disk (A stars!) will be \(~40\) km/s
Why aren’t there more?

• Key idea: gas richness is the fundamental parameter
  
  Drives $\sigma/v$ and ‘clumpy star formation mode’

• Gas consumption time is SHORT

• RARE IN SPACE?
  
  e.g. cold accretion survives?

• RARE IN TIME?
  
  temporary blip in $f_{\text{gas}}$ e.g. delivered via minor merger?
Summary

• Clumpy turbulent thick disk formation scenario looks like a good bet (SF scale driven by Jean’s mass and Toomre instability)

• Evidence for local analogues
  
  clumps? similar properties to z~2 disks
  
  Same feeding mechanisms? Same turbulence origin?
  
  Why are they rare? Star-formation histories?

• Next few years:
  
  HST program! (Cycle 20). ALMA?
  
  Confirm local analogues beyond reasonable doubt – gas rich?
  
  Use as laboratory for high-z disk formation – thick stellar disks? IMF?