Observations of local Turbulent Disk Galaxies with GMOS

Karl Glazebrook
Vesto Slipher
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 vast numbers than had been supposed. These facts seem to suggest that the nebulae are the following products of the internal changes of the stars. 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 of parts in 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:

<table>
<thead>
<tr>
<th>Month</th>
<th>Date</th>
<th>Velocity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>17</td>
<td>—284 km.</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>15-16</td>
<td></td>
<td>296</td>
</tr>
<tr>
<td>December</td>
<td>3-4</td>
<td></td>
<td>308</td>
</tr>
<tr>
<td>December</td>
<td>29-30-31</td>
<td></td>
<td>—301</td>
</tr>
<tr>
<td></td>
<td>Mean</td>
<td></td>
<td>—300 km.</td>
</tr>
</tbody>
</table>

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.

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.

The slit of the spectrograph was placed over the nebula, 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 Lemaitre (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 Lemaitre 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
Disk Galaxies at z~0 and z>1

$z \approx 0$

$z \approx 2$
$z \sim 0$

**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, OBA stars

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

(Note thermal $10^4$K broadening of $H\alpha = 9$ km/s)
Galaxies in their dominance by several giant clumps and having no exponential light profiles or central red bulges.

The distinguishing characteristics of the main types that we classified are as follows:

- **Chain**
- **Clump cluster**
- **Double clump**
- **Tadpole**
- **Spiral**
- **Elliptical**

Galaxy morphology can vary with wavelength, so we viewed the other images. Lower resolution, so they do not reveal the same fine structure as the NICMOS images. Generally, the morphological classification does not change significantly with wavelength (e.g., Dickinson 2000) because it is based on only the most fundamental galaxy characteristics, such as elongation and number.

**Fig. 1**

Selection of eight typical galaxies for each morphological type: four in (a) and four in (b). Tadpole galaxies with obvious spiral structure. Binary galaxies, like our doubles, are unlike the clump clusters here. Binary galaxies, like our doubles, ple included galaxies with bulges and exponential-like profiles, galaxies "luminous diffuse objects," although some of their sample were discussed by Straughn et al. (2004). Tadpole galaxies with exponential-like disks, evident spiral structure if they have low inclination, and usually a bulge or a nucleus. Edge-on spirals have relatively flat emission from a midplane, and often extended emission perpendicular to the midplane, and often extended emission perpendicular to the midplane. Elliptical galaxies. Images are at $z \sim 2$.

**Fig. 2**

<table>
<thead>
<tr>
<th>Type</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chain</td>
<td>169, 170, 1428, 401, 3458+3418</td>
</tr>
<tr>
<td>Clump cluster</td>
<td>6486, 4807, 7230, 9159</td>
</tr>
<tr>
<td>Double clump</td>
<td>637, 4072, 5098, 5251</td>
</tr>
<tr>
<td>Tadpole</td>
<td>3058, 8614, 5358, 6891</td>
</tr>
<tr>
<td>Spiral</td>
<td>3372, 3180, 4438, 8275</td>
</tr>
<tr>
<td>Elliptical</td>
<td>8, 4527, 4320, 5959</td>
</tr>
</tbody>
</table>

Figure 1 shows Figure 2. UDF or our own identification numbers from left to right in (a) and (b). $\sigma_z \sim 50$ km/s, $h_z \sim 1500$ pc.
Galaxy morphologies at z > 1

‘Chains’

‘Clump Clusters’

‘Doubles’

‘Tadpoles’

Elmegreen et al. 2005: galaxy morphologies in the HUDF
Clumps & Hα Kinematics

Wisnioski et al. (2011) [Keck/OSIRIS AO]
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 \( z = 0 \)
Gas richness?

23 galaxies z=1.1-3.0

\( <f_{\text{gas}}> \)

\( f_{\text{mol-gas}}(\text{CO}) \)

Tacconi et al. (2012)

\[ t_{\text{gas}} \sim \frac{10^{10} M_\odot}{100 M_\odot \text{yr}^{-1}} = 0.1 \text{ Gyr} \]
90% of the inflow is channelled through the streams (blue), at a rate that seems to be generic in massive haloes at high redshift, and is a feature of the cosmic web that deserves an explanation. Two of the streams radially seem to penetrate the inner disk, seen edge-on. The radial flux is the gas density and the virial radius.

The map shows radial flux for the galaxies with a box of side length 320 kpc. The colours refer to inflow rate per solid angle is \( \frac{v}{r} \). The entropy, \( \log (\frac{v}{r}) \), is the characteristic Press-Schechter halo mass, \( M_{v} \), in units of the characteristic scale of nonlinear clustering, i.e., the Press-Schechter halo mass. Because the cooling there is more efficient, the SFGs lie well above the merger curve even if \( z > 2.5 \). From the difference between the two curves of Fig. 4, we learn that the majority of the gas supply to the inner galaxy is driven by smooth streams. Thus, 'SFG' could also stand for 'stream-fed galaxies'.

The desired cumulative abundance, \( M_{\text{hit}} \), lies safely above the horizontal curve marks the robust threshold mass for a stable shock based on spherical symmetry. The inclined solid curve is the conjectured upper limit for cold streams, valid at redshifts higher than 5.

However, the central galaxy is fed by a clump with mass \( M_{\text{clump}} \), as distinct from 'smooth' flows, which include the mass is flowing in as mergers and the rest as smoother flows. Thus, 'SFG' could also stand for 'stream-fed galaxies'.

By analysing the clumpiness of the gas streams, using the sharp feature of the cosmic web that deserves an explanation. Two of the streams radially are to be seen during a merger. The fact that the SFGs lie well above the merger curve even if \( z > 2.5 \). From the difference between the two curves of Fig. 4, we learn that the majority of the gas supply to the inner galaxy is driven by smooth streams. Thus, 'SFG' could also stand for 'stream-fed galaxies'.

Dekel et al. (2009) (see also Keres et al., van der Voort et al.)

Redshift \( z \)
Local (z~0.1) Analogs of turbulent disks?

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Thanks to the SPIRAL and WiFES IFS instruments!

Andy Green (AAO)
High H\textalpha{} SDSS galaxies?

Green et al. (Nature 2010)
Turbulent disks at z~0?

1) disk kinematics?
Systematic errors will be largest for objects with complex kinematics and smallest for rotating disks. The dashed line in Panel B shows the stellar mass Tully-Fisher relation. The solid lines show the relations of Pizagno et al. and Green et al. for different observable bands.

For all three methods, a single circular velocity must be inferred at the disk scale lengths from disk fitting. Points are coded by their respective bands.

The Tully-Fisher relation for our sample in a variety of different bands.

The Tully-Fisher relation compares the circular velocity with the absolute magnitude.


Karl Glazebrook, SUT
Friday, 3 August 12
2) Are they clumpy?
Yes! In SF maps
Keck OSIRIS
Paschen $\alpha$ maps
(2-3 arcsec FOV)
Is the stellar mass clumpy?

**Gemini South Adaptive Optics Imager (GSAOI)**

Research School of Astronomy and Astrophysics  
Institute of Advanced Studies  
Australian National University

**GSAOI: McGregor et al.**

First Light!

Seeing limited 2 arcsec  
Classical AO  
GeMS

**Latest Developments:**

- GSAOI passes critical design review  
- GSAOI work progresses despite bushfires  
- RSAA wins GSAOI competition
3) Are they gas rich?

Don’t know – ALMA time please!
4) Are the stars in a turbulent disk?

Testing stellar kinematics using Gemini/GMOS IFU
**Velocity Map**

*SPIRAL Hα em.*

**SDSS gri**
Gemini Hβ emission
HfluxHz_20-2 H-gamma Rotation Curves

- Red circles: Stars
- Blue circles: Gas

Velocity (km/s) vs. Projected Distance (kpc)
Prediction: velocity dispersion of stellar disk (A stars!) will be \( \sim 40 \text{ km/s} \)
Summary

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

• Next few years:
  GMOS - stellar kinematics – YOUNG thick stellar disk?!
  HST program! (Cycle 20). ALMA?
  GSAOI - clumpy morphologies (K-band)
  ALMA - molecular gas