Planetary Nebulae in Spiral Galaxies: Shedding some Light on Dark Matter

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George Greaney, OGS 14.5"
GMOS Team, Gemini

A. Block, NOAO/AURA/NSF

VLT ANTU + FORS1, ESO

NASA, ESA, CFHT, NOAO
A Riddle

Look at a spiral—what do you see?
Stars zooming ‘round in the galaxy.
Their motions indicate total mass,
But how much is DM, stars, and gas?
Study motions in and out—first find
Monochromatic stars. (That’s my kind.)
Find us, get our velocities, then
Determine disk mass. I’m a PN!

(Planetary Nebula)

(Based on a figure from *The Milky Way as a Galaxy*, 1990)
What is a Planetary Nebula?

- Nothing to do with planets
  - Late 1700’s: stellar or nebulous
    - Spiral shape
    - Greenish and roughly round
- Late stage in evolution $M < 5M_\odot$
  - Short stage (~25,000 yrs)
  - Expanding shell of gas around a soon-to-be white dwarf
  - Gas emits at characteristic λ’s:
    - [O III]: 5007 Å and 4959 Å
    - Hα: 6563 Å and Hβ: 4864 Å

(H. Bond et al., Hubble Heritage Team, ESA, NASA)

(R. Sahai, Hubble Heritage Team, ESA, NASA)

(B. Balick et al, WFPC2, HST, NASA)

(NASA, ESA, & J. Gitlin)

(H. Bond et al., Hubble Heritage Team)
Why study Spiral Galaxies?

We live in one!

GMOS Team, Gemini

Milky Way
Why study Spiral Galaxies?

Look at a spiral—what do you see?
Stars zooming ’round in the galaxy.
Their motions indicate total mass,
But how much is DM, stars, and gas?

Assume a Constant Disk Mass-to-Light Ratio

Independent Method to Determine Distribution of Mass in the Disk

(Based on a figure from The Milky Way as a Galaxy, 1990)
My Project: PN Kinematics & Disk Mass

The orbits of old disk stars oscillate in $z$ according to

$$\sigma_z^2 = KG\Sigma(R)h_z$$

- $\sigma_z$ = the velocity dispersion in $z$
- $K$ = a constant, based on $\rho(z)$
- $\Sigma(R)$ = the disk mass surface density
- $h_z$ = the disk scale height

Since

a) a disk’s surface brightness declines exponentially with radius, $R$
b) spiral disks are supposed to have a constant $M/L$ and constant $h_z$

$\sigma_z$ should decline exponentially with $R$
Why use PNe to Study Disks?

- PNe are found in outer regions
- Complement absorption line spectroscopy
- Representative of old galactic disk
- “Easy” to find ([O III] $\lambda$5007 emission)
  - 1<sup>st</sup> step: Imaging & some science
- Precise spectroscopic velocities (~3 km s$^{-1}$)
  - 2<sup>nd</sup> step: Spectroscopy
How do we find PNe?

- Image the galaxy in several filters:
  - Reduce the images
  - Blinking Method
    - Find objects clearly on-band but not off-band

- Determine locations (RA & Dec) & magnitudes
- Need follow-up spectroscopy to get velocities

\[ [\text{O III}] \lambda 5007 \ (50 \text{ Å FWHM}) \]
\[ \text{H} \alpha + [\text{N II}] \ (75 \text{ Å FWHM}) \]
>1000 New Extragalactic PNe
>1000 New Extragalactic PNe

M33

M83

M101

IC 342

M74

M94
Science from Photometry

- PN Luminosity Function (PNLF) Distances
  - Recognized as a high-precision method
  - My distances agree well with literature values

However, the main goal is the kinematic study.
Follow-Up Spectroscopy

• Observations
  - Use Hydra with WIYN or CTIO 4-m
  - Multiple setups w/ 30-45 min exposures
  - Target as many PNe as many times as possible
  - Also target the blank sky, some miscellaneous objects, and random positions

2 INTRODUCTION
(from the Hydra manual)

Hydra derived its name from the resemblance of the fiber cable to the fresh water polyp of the genus Hydra. The complexity of the instrument, however, may make inexperienced users feel that the name was selected for the following definition:

Hydra n. A multifarious source of destruction that cannot be eradicated by a single attempt.¹

We certainly hope that this is not the case. As Hercules required planning and perseverance in conquering the mythical monster Hydra, so should users of the Hydra instrument likewise take the time and effort to carefully plan their strategy and be well prepared for the observing process. In that manner, Hydra shall not be a foe, but rather a friend, capable of providing a wealth of valuable astronomical data.

¹ The American Heritage Dictionary of the English Language
\[ \sigma_z^2 = KG \Sigma(R) h_z \]
THINGS to the rescue!

THINGS
(The HI Nearby Galaxy Survey)

IC 342
M74
M94
M83
M101
The Raw Velocities
Residual PN Velocities

M33
M83
M101
IC 342
M74
M94
Now we can answer some questions...

- Is the scale height (thickness) constant with radius?
  - It looks constant in some galaxies but flares in others

**IC 342**

**M94**
Now we can answer some questions...

- **Is the scale height (thickness) constant with radius?**
  - It looks constant in some galaxies but flares in others

- **Does the Mass-to-Light ratio stay constant?**
  - It looks constant in some galaxies but increases in others?
  - Hard to say because of uncertainty in light dropoff and $h_z$

Simulation results of a disk accreting a satellite
(S. Kazantzidis, private communication)
Now we can answer some questions...

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- Does the Mass-to-Light ratio stay constant?
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  - Hard to say because of uncertainty in light dropoff and $h_z$

- Are disks maximal?
  - It appears to vary with Hubble type such that early spirals are closer to being maximal than late spirals

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>$h_R$ (kpc)</th>
<th>$h_z$ (pc)</th>
<th>$M/L_R$</th>
<th>$\epsilon^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 342</td>
<td>Scd</td>
<td>4.24</td>
<td>500</td>
<td>0.4 ± 0.2</td>
<td>~0.2</td>
</tr>
<tr>
<td>M101</td>
<td>Scd</td>
<td>4.99</td>
<td>600</td>
<td>0.6 ± 0.3</td>
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<tr>
<td>M83</td>
<td>SBC</td>
<td>2.45</td>
<td>400</td>
<td>1.0 ± 0.5</td>
<td>~0.5</td>
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<tr>
<td>M74</td>
<td>Sc</td>
<td>3.17</td>
<td>400</td>
<td>1.5 ± 0.3</td>
<td>~0.4</td>
</tr>
<tr>
<td>M94</td>
<td>SAB</td>
<td>1.22</td>
<td>300</td>
<td>2.0 ± 0.4</td>
<td>~1</td>
</tr>
</tbody>
</table>

$\epsilon$: measure of disk "maximalness"
Now we can answer some questions...

- Is the Mass-to-Light ratio constant?
  - It looks constant in some galaxies but increases in others?
  - Hard to say because of uncertainty in light dropoff and $h_z$

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- Are Dark Matter halo rotation curves better fit by NFW or pseudo-isothermal (ISO) models?
  - As with low surface brightness galaxies and dwarf galaxies, ISO models fit the results much better than NFW models.
What is happening in the outskirts?

Satellite accretion? (AKA Galactic cannibalism!)
Conclusions

- Planetary Nebulae are dying low-mass stars
- They are excellent tools for studying nearby spiral galaxies
- >1000 new PNe in 6 spirals yield reliable distances
- Kinematic analysis yields interesting results:
  - $M/L$ of the inner $\sim 3$ scale lengths is roughly constant
  - Early spirals have higher $M/L$ than late types
  - Early spirals are closer to being maximal than late types
  - Isothermal models fit DM halos better than NFW models
  - Outside of $\sim 4$ scale lengths, $\sigma_z$ declines very slowly (if at all)
- Could be evidence of satellite accretion
Thanks to...

- Family & friends for support and encouragement
  - Including my extended PSU & Lowell Astro families
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- USNOFS Image & Catalogue Archive, NED, THINGS, NASA ADS
- & You (for attending my talk) 😊
Questions?

SATURDAY April 16 only
SUNSET UNTIL 11PM

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