Halo Gas Velocities Using Multi-slit Spectroscopy

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Thesis Proposal, Fall 2009
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Outline

• Diffuse ionized gas; galaxy halos

• Origin of halo – galactic fountain vs. accretion observations and modeling

• Project proposal – nearby, edge-on spirals
  multi-slit spectroscopy of Hα emission
  UV data from GALEX – extent of dust comparison with HI data
  extent, kinematics of ionized halo gas lagging halo, velocity gradients implications for outflow vs. infall

• Timeline
Diffuse Ionized Gas

- Edge on spirals (Hα, NII, SII)
- Thick, ionized gas disk (DIG)
- Extends into halo
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- DIG correlated with SFR in disk (e.g. Rand 1996, Hoopes et al. 1999)
**Diffuse Ionized Gas**

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**NGC 891**: smooth, extended DIG layer; up to 7kpc above plane (Hoopes & Walterbos 1999)

- high SFR (3.8 Msun/yr) (Popescue 2004)
- puff up layer; disk stars ionize it
Diffuse Ionized Gas

(Hoopes et al. 1999, Rand 1996)

• “Normal” galaxies, moderate SFR

• patchy DIG; filaments, loops
  - concentrated near nucleus

• heights 1-3 kpc above disk

• low SFR – not much DIG

NGC 4013, Hα
Radio Continuum Halo

- NGC 891 – radio halo coincides with Hα halo  
  (Rand 1996)

- NGC 5775 – radio emission coincides with Hα filaments  
  (Dettmar 1992)
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- high SFR → massive stars → SNe → CRs → radio emission

- CRs easily swept up in stellar winds (Rand et al. 1996)
  - transported to halo
  - plausible ionization source (along with OB disk stars)
Ionization Source

- SNe are main player
  - but not enough SNe to account for all ionization (MWG Reynolds layer)
  (Hoopes et al. 1999)
Ionization Source

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• OB stars contribute
  - can photons reach several kpc above disk?
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  - NGC 891: photoionization models can't simultaneously reproduce line ratios
    \([\text{NIII}]/\text{H}\alpha, [\text{SII}]/\text{H}\alpha, [\text{HeI}]/\text{H}\alpha\) (Rand 1997)

  - observed ratios indicate soft spectrum; unexpected if massive stars are significant source of ionization (Rand 1997)
X-ray Halo

- NGC 4631: Chandra observations – $6 \times 10^5$ K halo component

- Soft x-ray halo coincides with Hα halo  
  (Wang et al. 1995)

- Cooling of $6 \times 10^5$ K gas – ionization source for upper halo?  
  (Martin & Kern 2001)
Galactic Fountain

• Origin of halo?
  - outflow (was) favored
    (Shapiro & Field 1976)

• SNe eject hot gas out of disk
  - rotating “too fast”
  - moves outward; slows down
  - rotational velocity decreases with height
Galactic Fountain

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• Lagging halo – first observed in NGC 891
  DIG (Rand 1997); HI (Swaters et al. 1997)

• Velocity gradients: 10s km/s/kpc for small sample of edge-ons
  (Rand 2005, Heald et al. 2006, Heald et al. 2007)
  - higher SFR – higher DIG layer scale height – lower gradient
  - typical DIG scale heights ~1-2 kpc
Models

• Simple ballistic models
  - galactic fountain
  - accurately predict extent of DIG
  - reproduce lag but not velocity gradient
Models

• Collins et al. (2002)

  - model inputs:
    DIG scale height,
    galaxy rotation curve

  - NGC 5775, NGC 891:
    high SFR, extended DIG
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  - NGC 5775: model matches lower DIG layer; 
faster gas than observed at $z = 5$ kpc (systemic) 
  (gradient too low at high $z$)
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  - NGC 891: model gradient too high; gas rotates too slowly
    1-4.5 kpc – observed drop = 30 km/s
    model predicts 85 km/s drop
    disk-halo interaction cause higher gas velocities?

Collins et al. 2002. NGC 891: model, H\( \alpha \), NII
Models

- Heald et al. (2006): NGC 891
  - data: \(~17 \, \text{km/s/kpc}\)
  - model: 1-2 km/s/kpc

Ionized gas rotates too quickly.

Average rotational velocity at each height

Circles: 1.2 - 2.1 kpc; crosses: 3.0 – 4.8kpc

Heald et al. 2006
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  - ballistic model, neutral halo, NGC 891
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- **Fraternali & Binney (2006)**
  - HI halo, NGC 891, continuous flow disk \( \rightarrow \) halo
  - model gas rotates too quickly

Circles: 1.2 - 2.1 kpc; crosses: 3.0 – 4.8kpc
Average rotational velocity at each height
Heald et al. 2006
Models

- General consensus:
  - low-angular momentum component
  - drag between disk/halo
Models

• General consensus:
  - low-angular momentum component (accretion)
  - drag between disk/halo

• Fraternali et al. (2007)
  - modeled slower rotating hot halo gas interacting with fountain gas (NGC 891)
  - better velocity gradients
  - but hot halo spins up in $t < 1$ million yrs
  - insufficient to explain observed lag

Fraternali et al. 2007: channel maps, NGC 891
Evidence for Accretion

• Need low-angular momentum component to slow down gas

• NGC 2403 – coherent filaments, counter-rotating clouds
  (Fraternali et al. 2001)

  - hard to explain with fountain; accretion likely source
  - clouds – like HVCs in MWG (sub-solar metallicity, little dust)
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• NGC 6946 – hole in out disk, HI plume
  (Boomsma et al. 2005)
  - fountain or collision; accretion of companion
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- NGC 253 – 10 kpc plume, counter-rotating gas
  (Boomsma et al. 2005)

- NGC 891 – 22 kpc plume, counter-rotating clouds
  (Oosterloo et al. 2007)
  - most of halo from disk; small amount from accretion
Evidence for Accretion

• More interactions observed (more sensitive instruments) (van der Hulst & Sancisi, 2005)

  - accretion of small amounts of HI common?
Evidence for Accretion

• More interactions observed (more sensitive instruments) (van der Hulst & Sancisi, 2005)
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• Fraternali & Binney (2008) modeled ballistic flow interacting with cold, infalling clouds – NGC 891, NGC 2403
  - assumed accretion rate similar to each galaxy's SFR
  - accurately predicts velocity gradients
  - 10-20% of halo material from accretion, rest from fountain

Fraternali & Binney 2008: NGC 891
Project Proposal

• Origin of halo gas – Outflow from disk? Infall from IGM?

• Spectroscopic observations of Hα
  - determine characteristics, extent, kinematics of DIG
  - look for lagging halo, counter-rotating gas
  - constraints for models of halos

• GALEX data
  - dust distribution – metal content

• Compile Hα data, UV data, HI data
  - put in context of question of halo origin
Project Proposal

- Target list: range of Hubble type and SFR
  - $L_{\text{FIR}}$ – luminosity from IRAS satellite, star formation tracer
  - $D_{25}$ – diameter at which galaxy is $25^{\text{th}}$ magnitude
- 10 targets; 10 hours per field

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Type</th>
<th>$V_{\text{hel}}$ (km s$^{-1}$)</th>
<th>Distance (Mpc)</th>
<th>$L_{\text{FIR}}/D_{25}^2$ ($10^{40}$ erg s$^{-1}$ kpc$^{-2}$)</th>
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Spectroscopy

- Traditional way to detect DIG: single slit spectroscopy
  - measure extent, velocity along one slit
  - kinematics of large part of halo – time consuming
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• Multi-slit setup
  - series of slits – multiple spectra simultaneously
  - measure extent, velocity at several radii in single exposure
  - 2D velocity field (R, z)
Multi-slit Spectroscopy

- Slitmask
  - uniform, parallel slits
  - narrowband filter (25A FWHM) to isolate particular spectral line and prevent overlapping spectra
  - 16 slits, 2” wide, 4.5' long, 15” apart
  - 11 slits, 1.5” side, 4.5' long, 22.5” apart
  - 6570A, 6580A, 6590A filters – redshifted Hα
Multi-slit Spectroscopy

- Dual Imaging Spectrograph at APO (red side)
- Filterwheel – mount single slit and multi slit
- Center on target with single slit; apply offsets; rotate multi slit into place
- Slits perpendicular to major axis – velocity as function of height at several radii in one exposure
Continuum overlaps; Spectral lines do not.
For each slit, use IRAF to measure wavelength at various heights

Calculate velocity
Empirically calculate errors
Use same IRAF routine on sky frames

Check for consistency along each line
Check from line to line – should have same separation

See how brightness affects accuracy
Velocity (km/s) is on the x-axis.

Distance from the plane (kpc) is on the y-axis.
Multi-slit Spectroscopy

- Extinction or HII region along our LOS can affect velocity measurement

Multi-slit Spectroscopy

• Extinction or HII region along our LOS can affect velocity measurement

• HI – possible warped outer disk
  - projected along LOS, appears as thick HI disk
  - Hα – not much ionized gas in outer disk; warp not a problem

NGC 4244

Hα and HI velocities along the mid-plane of the galaxy

NGC 891
Galaxy Evolution Explorer (GALEX)

Extra-galactic all-sky survey (UV)

Dust scatters light from galaxy forward into our line of sight

Archive images
Compare UV to optical light

- Formed from gas processed by stars (metallicity)
- If dust high above plane – outflow from disk (processed by stars)
- If dust lacking at large distances – infall (metal poor)
Summary

• Spectroscopy of Hα
  - determine which galaxies have extended emission
  - how emission correlates with SFR, HI

  - kinematics of Hα-emitting gas
    - lagging halo; velocity gradient
    - comparison to HI – are ionized and neutral H correlated?

• UV data from GALEX
  - look for evidence of dust in halo gas
    - amount of dust is related to metal content; origin

• Compare Hα, HI, and GALEX data
  - put in context of overall picture of halo formation
Timeline

• Q4 2009 – Finish observations of NGC 891

• Q1 2010 – Present results for NGC 891, NGC 4631 at AAS (Washington, D.C.) and at NM Symposium
  – Observe 2 targets

• Q2 2010 – Paper I: Halo Gas Velocities of NGC 891, NGC 4244, NGC 5907, NGC 4631
  – Observe 2 targets
  – Users Guide for Multi-slit Spectroscopy at APO

• Q3 2010 – Paper II: Distribution of Dust in NGC 891 and NGC 4631 from GALEX Archival Data

• Q4 2010 – Finalize results for Q1 and Q2 data; dissertation

• Q1-Q2 2011 – Finish observations; dissertation

• Summer 2011 – Graduate
sky frame and sci frame with skylines still in it

skylines are at known wavelengths
use those as calibration point to determine absolute velocities

...but aren't arc lines at known wavelengths, too? (well, the center slit arc line)

vel's are relative to each other – can measure gradient this way
BUT why doesn't this give absolute vel??
Halo Gas Velocities

Velocity (km/s) is on the x-axis.
Distance from the plane (kpc) is on the y-axis.

3.5 hours of exposure time.