Galactic Winds Driven by Supernovae and Radiation Pressure

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SESAPS, Nov 10, 2016
Galactic Winds are observed both at low- and high- $z$
Arp 220

Hubble

Subaru

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NGC 253

ALMA (Bolatto’s slides)

200 km/s

X-ray and Hα

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Galactic Winds are Important

- Re-shape the galaxy luminosity function/stellar mass function
- Determine the chemical evolution and the mass-metallicity relation
- The most extreme manifestation of the feedback between SFR and ISM
Galaxy Stellar Mass Function

Baldry et al. 2008

Silk 2012

Baldry et al. 2008
Feedback on Galaxy Evolution

Hopkins et al. 2012
Multi-Phase Structure of Galactic Winds

NGC 253

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Westmoquette 2013
Multi-Phase Structure of Galactic Winds

M82

Strickland & Heckman 2009

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Multi-Phase Structure of Galactic Winds

Interface of wind cavity with surrounding cold gas produces Hα, PAH emission, high dust temperatures
Coincidence of Hα, dust, 8μm with CO

H2 becomes HI as it leaves galaxy
Mass profiles

H2 and HI flow along minor axis
Velocity gradients along minor axis

HI and H2 confine outflow for several kpc
Double peaked profiles at high latitude, high dust temperatures

Dusty material forms a spheroidal halo near galaxy, mostly mixed with HI at large distances
Finite extent, round shape, mass profiles

H2 expelled over wide angle
Angular momentum flow lines and slowing rotation, round morphology

Dust and molecular (as HI) material must fall back
Mass conservation and finite extent of emission

M82

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Leroy et al. 2015
M82 : Observation

Hα (subaru)
Vc ~ 600 km/s

CO emission (from Veilleux’s 2014 slides)
Vc ~ 100 km/s

disk
outflow

“tidal streamers”
Scenario for cloud acceleration

Legend:
- Starburst region
- Galaxy disk
- Velocity vectors
- X-ray emitting plasmas
- Entrained cooler gas

Cooper et al. 2008

Strickland Astro2010
Ram pressure of the Hot Flow

Ram Pressure Acceleration

Killed by hydrodynamical instabilities (Kleivin-Helmholz)

$V_{cool}$

$V_{hot}$

Cool/Cold Cloud

Hot wind driven by SN
Ram pressure of the Hot Flow

Ram Pressure Acceleration

Killed by hydrodynamical instabilities (Klevin-Helmholz)

If $t_{KH} < t_{acc}$, no significant acceleration!
Our Analytic Model

- Include Gravity
- Radial Acceleration of Cool Clouds
- Broad range of galaxy parameters

\[
\frac{M_c}{dt} = \dot{M}_{\text{hot}} V_{\text{hot}} \left(1 - \frac{V_c}{V_{\text{hot}}}\right)^2 \frac{A_c}{\Omega r^2} - \frac{G M_{\text{gal}}(r) M_c}{r^2}
\]

\[
t_{\text{KH}} \approx \kappa \left(\frac{\rho_c}{\rho_{\text{hot}}}\right)^{1/2} \frac{\Delta R}{V_{\text{hot}}}
\]
Na D survey

![Graph showing the relationship between Vc (km/s) and SFR (M⊙ yr⁻¹)]

- Dotted line: β=0.01
- Solid line: β=0.03
- Dashed line: β=0.1
- Dotted-dashed line: β=0.3
- Dashed-dotted line: β=1.0

Vc (km/s) is plotted on the y-axis, and SFR (M⊙ yr⁻¹) is plotted on the x-axis.
Cloud Acceleration/Destruction
Numerical Simulation

Scannapieco & Bruggen 2015
HOT WIND CANNOT EXPLAIN!

Hα (subaru)
Vc ~ 600 km/s

CO emission (from Veilleux’s 2014 slides)
Vc ~ 100 km/s
Radiation Pressure Driven Winds
Dust-Driven Stellar Wind (AGB star)

AGB star

dust formation zone

pulsational shocks

waves

flow instabilities

Credit: Peter Woitke
Radiation Pressure Driven Wind in Starbursts and SFG

Dusty Gas

UV light

IR light
Radiation Pressure Driven Wind in Starbursts and SFG

Dusty Gas

Thompson et al. 2005

UV light

IR light

Thompson et al. 2005

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Uniform Self-Gravitating Disk

-- Uniformly Bright Disk

-- Optically Thick (to IR)

-- Radiating at Eddington Limit
$v_\infty \sim 2\sqrt{\pi/2} - 1 v_{rot} \sim 1.5 v_{rot}$

$V_{max} \sim 3 V_{esc}$

$V_{mean} \sim SFR^{0.35}$

Match the observation!

Zhang & Thompson 2012
Gas-Radiation Interaction
Radiative Hydrodynamic Simulations

Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?
Gas-Radiation Interaction
Radiative Hydrodynamic Simulations

- **Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?**

\[
\frac{dp_{\text{wind}}}{dt} \sim (1 + \eta \tau_{\text{IR}}) \frac{L}{c}
\]
Gas-Radiation Interaction
Radiative Hydrodynamic Simulations

- Is Radiation Pressure on Dust Strong enough to Drive a Galactic Wind?

\[
\frac{dp_{\text{wind}}}{dt} \sim (1 + \eta \tau_{\text{IR}}) \frac{L}{c}
\]

- \( \eta \ll 1 \), (Krumholz & Thompson 2012, 2013)
- \( \eta = 1 \), analytic model (Murray, Quataert & Thompson 2015)
Gas-Radiation Interaction
Radiative Hydrodynamic Simulations

- Is Gas Turbulence important?
- Momentum Coupling between Radiation and Gas?
- We need a more sophisticated algorithm than previous numerical simulations.

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**Radiation-Pressure on Dusts: Radiative Hydrodynamic Simulations**

Set of Equations

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} + \mathbf{P}) &= \rho \mathbf{g} - \mathbf{S}_r(\mathbf{P}), \\
\frac{\partial E}{\partial t} + \nabla \cdot (E \mathbf{v} + \mathbf{P} \cdot \mathbf{v}) &= \rho \mathbf{g} \cdot \mathbf{v} - c \mathbf{S}_r(E), \\
\frac{\partial E_r}{\partial t} + \nabla \cdot \mathbf{F}_r &= c \mathbf{S}_r(E), \\
\frac{1}{c^2} \frac{\partial \mathbf{F}_r}{\partial t} + \nabla \cdot \mathbf{P}_r &= \mathbf{S}_r(\mathbf{P}),
\end{align*}
\]
Radiation-Pressure on Dusts: RHD Simulation

Flux Limited Diffusion

\[ F_r = -\frac{c\lambda}{\sigma_F} \nabla E_r \]

Levermore & Pomraning 1981
Radiation-Pressure on Dusts: RHD Simulation

Flux Limited Diffusion

\[ F_r = -\frac{c\lambda}{\sigma_F} \nabla E_r \]

Levermore & Pomraning 1981

Variable Eddington Tensor

\[ \hat{n} \cdot \nabla I = \sigma_F \left( \frac{a_r c}{4\pi} T^4 - I \right) \]

\[ f = \frac{P_r}{E_r} = \frac{\int I(\hat{n}) \mu_i \mu_j d\Omega}{\int I(\hat{n}) d\Omega} \]

\[ E_{rad} = \frac{4\pi}{c} \int_0^\infty J_\nu d\nu , \]

\[ F_{rad} = 4\pi \int_0^\infty H_\nu d\nu , \]

\[ P_{rad} = \frac{4\pi}{c} \int_0^\infty K_\nu d\nu . \]

Davis et al. 2014
Radiation-Pressure on Dusts: Simulation (Flux Limited Diffusion)

Sub-Eddington System

\[ f_{E,*} = \frac{\kappa_{R,*} F_*}{g c} \]
Radiation-Pressure on Dusts: Simulation (variable Eddington Tensor)

\[ f_{E,*} = \frac{\kappa_{R,*} F_*}{g c} \]
Gas Temperature

Davis et al. 2014

 SESAPS, Nov 10, 2016
Monte Carlo Method
Radiation-Pressure on Dusts: Simulation (variable Eddington Tensor)
Radiation-Pressure on Dusts: Simulation
(variable Eddington Tensor)
Wind-Radiation Interaction (FLD)

\[ \tau_* = 3 \]

\[ \tau_* = 10 \]

\( \text{flux} \)

no gravity

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Krumholz & Thompson 2013
Wind-Radiation Interaction (FLD)

$\tau_* = 3$

$\tau_* = 10$

Radiative Rayleigh-Taylor Instability (RRTI)

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Krumholz & Thompson 2013
Trapping Factor

\[ \frac{dp_{\text{wind}}}{dt} \sim (1 + f_{\text{trap}}) \frac{L}{c} \]

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Krumholz & Thompson 2013

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$\tau = 3$, VET

$\tau = 3$, FLD

no gravity

Zhang & Davis
in preparation

SESAPS, Nov 10, 2016
Trapping Factor

\[ \frac{dp_{\text{wind}}}{dt} \simeq (1 + f_{\text{trap}}) \frac{L}{c} \]
Radiation-Pressure-Driven Wind
Radiation-Pressure-Driven Wind

\[
\frac{d\rho_{\text{wind}}}{dt} \approx \left\{ 1 + \eta \tau_{\text{IR}} \left[ 1 - \frac{(f_{E,*})_0}{f_{E,*}} \right] \right\} \frac{L}{c}
\]

\[
f_{E,*} = \frac{\kappa_{R,*} F_*}{gc}
\]
Radiation-Pressure-Driven Wind

\[
\frac{dP_{\text{wind}}}{dt} \sim \left\{ 1 + \eta \tau_{\text{IR}} \left[ 1 - \frac{(f_{E,*})_0}{f_{E,*}} \right] \right\} \frac{L}{c}
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Radiation-Pressure-Driven Wind

\[ \frac{dp_{\text{wind}}}{dt} \approx \left\{ 1 + \eta \tau_{\text{IR}} \left[ 1 - \frac{(f_{\text{E},*})_0}{f_{\text{E},*}} \right] \right\} \frac{L}{c} \]

\[ f_{\text{E},*} = \frac{\kappa_{R,*} F_*}{gc} \]

\( \tau_\ast = 1, 3, 10 \)
\( \tau_{\text{IR}} = 1.8, 7.9, 48.5 \)
\( \eta = 0.90, 0.69, 0.47 \)
Radiation-Pressure-Driven Wind

\[ \frac{dp_{\text{wind}}}{dt} \approx \left\{ 1 + \eta \tau_{\text{IR}} \left[ 1 - \frac{(f_{E,*})_0}{f_{E,*}} \right] \right\} \frac{L}{c} \]

\[ f_{E,*} = \frac{\kappa_{R,*} F_*}{g c} \]

- Wind can be driven from a Sub-Eddington System
- Wind has the similar properties as it at the base of the system
LIRGs and ULIRGs

Table 5
Summary of derived average physical parameters based on 32.5 GHz continuum emission sizes*

<table>
<thead>
<tr>
<th>Galaxy Name</th>
<th>T$_{b33GHz}$ (K)</th>
<th>T$_{b1.4GHz}$ (K)</th>
<th>$\alpha_{CO}$</th>
<th>$\Sigma_{mol}$ (M$_{\odot}$ pc$^{-2}$)</th>
<th>$N_{H}$ (cm$^{-2}$)</th>
<th>$n_{mol}$ (cm$^{-3}$)</th>
<th>$\Sigma_{SFR}$ (M$_{\odot}$ yr$^{-1}$ kpc$^{-2}$)</th>
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<tr>
<td>CGCG 436-030</td>
<td>1.05E+03</td>
<td>4.37E+04</td>
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<td>NGC 3690 ****</td>
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LIRGs and ULIRGs

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<td>4.45E+04(1.80E+04)</td>
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<td>7.96E+03(3.21E+03)</td>
<td>8.68E+02</td>
<td>7.17E+12</td>
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<tr>
<td>UGC 08696</td>
<td>1.01E+02</td>
<td>3.44E+05</td>
<td>0.45</td>
<td>1.54E+04(8.84E+03)</td>
<td>1.92E+24</td>
<td>1.77E+03(1.02E+03)</td>
<td>1.14E+03</td>
<td>9.40E+12</td>
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<td>VV 340a</td>
<td>1.41E-01</td>
<td>1.31E+03</td>
<td>1.77</td>
<td>2.49E+02(5.66E+02)</td>
<td>3.12E+22</td>
<td>2.81E+00(6.38E+00)</td>
<td>3.61E+00</td>
<td>2.98E+10</td>
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<tr>
<td>VV 705</td>
<td>2.86E+00</td>
<td>9.02E+03</td>
<td>1.11</td>
<td>1.04E+03(1.47E+03)</td>
<td>1.31E+23</td>
<td>3.18E+01(4.48E+01)</td>
<td>4.17E+01</td>
<td>3.44E+11</td>
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<td>Arp 220</td>
<td>4.90E+02</td>
<td>1.15E+06</td>
<td>0.29</td>
<td>4.88E+04(1.91E+04)</td>
<td>6.11E+24</td>
<td>1.41E+04(5.52E+03)</td>
<td>7.33E+03</td>
<td>6.05E+13</td>
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<td>7.07E+01</td>
<td>2.60E+06</td>
<td>1.46</td>
<td>5.09E+02(2.61E+04)</td>
<td>6.52E+22</td>
<td>6.24E+00(1.06E+03)</td>
<td>1.51E+03</td>
<td>1.08E+12</td>
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<tr>
<td>IRAS 19542+1110</td>
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<td>1.67E+05</td>
<td>0.47</td>
<td>1.42E+04(8.40E+03)</td>
<td>1.78E+24</td>
<td>1.78E+03(1.05E+03)</td>
<td>1.12E+03</td>
<td>9.26E+12</td>
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<td>CGCG 448-020</td>
<td>2.14E+00</td>
<td>7.03E+03</td>
<td>1.31</td>
<td>5.90E+02(2.10E+03)</td>
<td>7.38E+22</td>
<td>2.10E+01(3.59E+01)</td>
<td>4.76E+01</td>
<td>3.59E+11</td>
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<tr>
<td>IRAS 21101+8810</td>
<td>6.43E+00</td>
<td>1.74E+04</td>
<td>0.78</td>
<td>2.86E+03(2.88E+03)</td>
<td>3.58E+23</td>
<td>1.87E+02(1.89E+02)</td>
<td>1.43E+02</td>
<td>1.18E+12</td>
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<tr>
<td>IRAS P23365+3604</td>
<td>4.77E+01</td>
<td>1.95E+05</td>
<td>0.36</td>
<td>3.13E+04(1.42E+04)</td>
<td>3.91E+24</td>
<td>3.94E+03(1.79E+03)</td>
<td>1.40E+03</td>
<td>1.15E+13</td>
</tr>
</tbody>
</table>

LIRGs and ULIRGs

\[ f_{E,*} \sim 0.3 \quad \tau_* \sim 30 \]
\[ f_{E,*} \sim 0.8 \quad \tau_* \sim 230 \]
LIRGs and ULIRGs

\[
\frac{dp_{\text{wind}}}{dt} \sim \left\{ 1 + \eta \tau_{\text{IR}} \right\} \left[ 1 - \frac{f_{E,*}(0)}{f_{E,*}} \right] \frac{L}{c}
\]

- \( f_{E,*} \approx 0.3 \)
- \( \tau_* \approx 30 \)
- \( f_{E,*} \approx 0.8 \)
- \( \tau_* \approx 230 \)

Arp 220

Mrk 231

SESAPS, Nov 10, 2016
Conclusions

- Cool gas with temperatures $100 - 10^4$ K seen in galactic winds cannot be accelerated to observed velocities by the ram pressure of a SN-driven wind.

- Some observation relations might be explained by dust-driven winds.

- In VET radiation may accelerate dusty gas even from an initial sub-Eddington system. The momentum coupling between radiation and gas is a function of optical depth.

- Radiation Pressure on dust is an important mechanism to drive galactic winds.