Supernova Remnants (SNRs) offer the means to study supernova explosions and evolution at sub-parsec scales. Toward this end, we have begun a systematic, statistical analysis of a large sample of remnants. In this work, we are investigating the symmetry of the radio continuum emission produced at the forward shocks. For this work we are selecting our sample from supernova remnants fully imaged by the HI, OH, Recombination Line (THOR) Survey and were detected. These sources are shown in Figure 1.

The THOR Survey covered galactic longitudes from 14.5 to 67.4 degrees and latitudes between +/- 1.25 degrees. Out of the SNRs located in this quadrant of the Galaxy, we inspected them and identified 59 that were fully imaged and were detected.

We measure the symmetry of our sample using a multiple analysis technique called the power-ratio method. This method replaces the mass surface density. The powers $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$ over the aperture radius $R$. We divide the powers $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$ by $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$, respectively. This result suggests that the morphology can have different degrees of asymmetry at earlier stages/smaller radii, while older SNRs with large radii are asymmetric. As the radio data analyzed were tracing HI and H$\alpha$ emission, there does not appear to be a trend between these parameters. The former measures ellipticity/elongation, and the later quantifies mirror asymmetry. The sample spans a range of values in this diagram, and there does not appear to be a trend between these parameters.

Current and Future Work

The assumption that radius is a proxy for age neglects the effects of different or inhomogeneous density mediums. Nonetheless, given the unknown ages of the SNRs the radii are the best indicator of evolutionary stage. The importance of the interstellar medium.

Lopez et al. (2009, 2011; Peters et al. 2013) found that Type Ia SNRs are more evolve with age. We measure the symmetry of our sample using a multiple analysis technique called the power-ratio method. This method replaces the mass surface density. The powers $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$ over the aperture radius $R$. We divide the powers $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$ by $P_{\text{0}}$, $P_{\text{2}}$, and $P_{\text{3}}$, respectively. This result suggests that the morphology can have different degrees of asymmetry at earlier stages/smaller radii, while older SNRs with large radii are asymmetric. As the radio data analyzed were tracing HI and H$\alpha$ emission, there does not appear to be a trend between these parameters. The former measures ellipticity/elongation, and the later quantifies mirror asymmetry. The sample spans a range of values in this diagram, and there does not appear to be a trend between these parameters.
Group & Collaborators

Katie Auchettl
Prof @ UMelbourne

Tyler Holland-Ashford
OSU PhD Student

Grace Olivier
OSU PhD Student

Ness Mayker
OSU PhD Student

Sebastian Lopez
OSU PhD Student

Other collaborator folks: Anna Rosen (Harvard), Isha Nayak (STScI), Megan Reiter (UK ATC), Dustin Nguyen (OSU), Tim Linden (Stockholm), Todd Thompson (OSU), Adam Leroy (OSU), Mark Krumholz (ANU), Alberto Bolatto (Maryland), Enrico Ramirez-Ruiz (UCSC)
Conclusions

Stellar feedback, the injection of energy and momentum by stars, is important on small (~1 pc) and large (>10 kpc) scales.

There are many challenges to assessing feedback: 1) dynamic range; 2) need observational constraints; 3) where is the energy/momentum deposited?; 4) there are many mechanisms that vary with time & conditions.

There are observational and theoretical solutions to each problem, and a lot of progress in the last 5 years assessing dynamical role of feedback on small & large scales.

Multiwavelength approach enables evaluation of comparative role of feedback modes versus e.g., stellar age, conditions.

X-ray and gamma-ray observations constrain presence / properties of galactic outflows from star-forming galaxies.
Importance of Feedback

Identified in the late 1970s that stellar feedback is necessary to form realistic disk galaxies (White & Rees 1978)

Stellar and Bulge mass 10x too big (Keres al. 2009)

Comparison at z=2

HIGH VS. LOW THRESHOLD SIMULATIONS

With higher threshold, the disk at z=2 is

- 50% larger
- 30% less massive
- 30% higher gas fraction
- 5x lower density at r < 1 kpc

Stellar and Bulge

Guedes et al. 2011

Yes Feedback

No Feedback

Tuesday, October 19, 2010
Importance of Feedback

Large Scale (>kpc)

Realistic stellar masses and bulges in galaxies (e.g., White & Rees 78; Keres+09)

Formation of bulgeless dwarf galaxies (e.g., Mashchenko+08; Governato+10)

Galaxy luminosity function and the mass-metallicity relation (e.g., Kauffmann+94; Cole+1994; Somerville & Primack99)

Star formation efficiency on galactic scales (e.g., Kennicutt98)

Kpc-scale galactic winds (e.g., Veilleux+05)

---

Figure 1.

Figure 2.
Importance of Feedback

Large Scale (>kpc)

Realistic stellar masses and bulges in galaxies (e.g., White & Rees78; Keres+09)

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Kpc-scale galactic winds (e.g., Veilleux+05)

Small Scale (<100 pc)

Creates ISM phase structure (e.g., McKee & Ostriker77)

Low star formation efficiency in giant molecular clouds (e.g., Zuckerman & Evans74; Krumholz & Tan07)

Disruption & destruction of GMCs (e.g., Matzner02; Krumholz+06)

Drives turbulence (e.g., Mac Low & Klessen04; Offner & Liu16)

Triggers star formation (e.g., Elmegreen98; Deharveng+05)
In the Feedback Loop - Small Scales

Stellar feedback: the injection of energy & momentum by stars

Protostellar Jets
Quillen+05, Cunningham+06, Matzner07, Nakamura+08, Cunningham+09, Wang+10, Krumholz+12, Offner+14, Li+15, Matzner+15, Bally16, Offner+17, Murray+18
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Radiation Pressure (direct and dust-processed)
Jijina+96, Krumholz&Matzner09, Fall+10, Krumholz+10, Draine+11, Murray+11, Skinner+15, Gupta+16, Kim+16, Raskutti+16, Rodriguez-Ramirez+16, Raskutti+17, Ali+18, Kim+18, Krumholz18, Tsang+18

Photoionization Heating
Whitworth79, Dale+05, Dale+14, Geen+16, Gavagnin+17, Ali+18, Haid+18, Kim+18, Kuiper+18, Shima+18

Stellar Winds
Yorke+89, Harper-Clark+09, Rogers+13, Dale+14, Goldsmith+17, Rahner+17, Haid+18, Naiman+18, Wareing+18
Simulating Photoionization + Winds

Dale et al. 2014
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Supernovae
Rogers+13, Kim & Ostriker15, Martizzi+15, Walch+15, Geen+16, Haid+16, Kortgen+16, Gentry+17, 18, Zhang+18

Cosmic Rays
Stellar winds and supernovae shock-heat gas to $10^7$ K temperatures and are observable in X-rays.
Cosmic-Ray Feedback

~10% of $E_{SN}$ goes into accelerating particles up to TeV energies at the forward shock (cosmic rays)

1. CRs can drive galactic winds
2. CRs can suppress star formation
3. CRs can affect wind properties: CR winds are cooler, multiphase, accelerated more gently
4. CRs can affect CGM properties: CGM is cooler and metal-enriched
Cosmic-Ray Feedback

References: Ipavich75, Breitschwerdt+91, Zirakashvili+96, Ptuskin+97, Everett+08, Jubelgas+08, Socrates+08, Everett+10, Samui+10, Wadepuhl+11, Dorfi+12, Uhlig+12, Booth+13, Hanasz+13, Salem+14, Girichidis+16, Liang+16, Pakmor+16, Ruszkowski+16, Simpson+16, Pfrommer+17a,b, Recchia+17, Ruszkowski+17, Wiener+17, Butsky+18, Chan+18, Farber+18, Girichidis+18, Heintz+18, Holguin+18, Jacob+18, Mao+18, Samui+18, Butsky+18, Chan+19, Hopkins+19, Brüggen+20, Buck+20, Bustard+20, Butsky+20, Dashyan+19, Hopkins20abcd, Jana+20, Ji+20….
Feedback is one of the biggest uncertainties in star and galaxy formation models today.
Feedback Challenge #1: Dynamic Range

Solutions:
Observations: Study MW and nearby galaxies where all scales are observable
Theory: Zoom-in simulations give pc resolution
Feedback Challenge #2: Need Observational Constraints

Radiation Pressure (direct and dust-processed)
  Optical/UV/IR

Photoionization Heating
  Optical/Radio

Stellar Winds
  X-rays

Supernovae
  X-rays/Radio

Protostellar Jets
  Optical/IR/mm

Cosmic rays
  Gamma-rays/Radio
Feedback Challenge #2: Need Observational Constraints - Solutions

Radio: Dickel+05; Infrared: Meixner+06; Optical: Smith+99;
X-ray: Snowden+94; Gamma ray: LL+21
Feedback Challenge #3: Where is Energy/Momentum Deposited?
Stars move.

46% of O stars and 10% of B stars are “runaway” (with $v > 30$ km s$^{-1}$)

OB stars travel 50-500 pc before exploding as SNe

Runaway stars are located in much less dense regions - leads to higher escape fractions

Kimm & Cen14
Feedback Challenge #3: Where is Energy/Momentum Deposited?

Solutions

Theory: Test different placement of SNe and compare simulation results to observables.
Feedback Challenge #3: Where is Energy/Momentum Deposited?

Walch et al. (2015)

Figure 5. Same as Fig. 4 but for run S10-KS-rand-nsg without self-gravity at $t = 50$ Myr (top) and at $t = 100$ Myr (bottom).

Figure 6. Same as Fig. 4 but for run S10-KS-clus with clustered SN driving at $t = 50$ Myr (top) and at $t = 100$ Myr (bottom).

Figure 8. Same as Fig. the run with peak driving S10-peak-KS at $t = 50$ Myr (top) and for mixed driving S10-mix-KS at the final snapshot of this run at $t = 43.6$ Myr (bottom).
Feedback Challenge #3:
Where is Energy/Momentum Deposited?

Solutions

Observations:
Use Atacama Large Millimeter/submillimeter Array (ALMA) data to show how close SNe are to molecular clouds (Mayker, Leroy, LL+ in prep)

Type Ia SNe preferentially occur in lower surface density locations far from molecular gas

Core-collapse SNe occur in higher surface density in/near molecular gas
Dominant feedback mode changes with time

Feedback Challenge #4: Many Mechanisms

...
Feedback Challenge #4: Many Mechanisms

In simulations, different mechanisms produce vastly different galaxies at $z \sim 0$ (Aquila Comparison Project: Scannapieco et al. 2011)

Major differences in:
- Morphology
- Radius
- Gas Fraction
- Stellar Masses
- Star Formation Histories

$M_{\text{stars}} \sim 4 \times 10^{10} - 3 \times 10^{11} \, M_{\odot}$

$SFR \sim 0.1 - 10 \, M_{\odot}/yr$
Feedback Challenge #4: Many Mechanisms

Solutions:

Theory: Incorporate many mechanisms; compare relative role of those mechanisms with e.g., age, mass, conditions

Rahner+17

Dale+14
Feedback Challenge #4: Many Mechanisms

Observations: Exploit multiwavelength data; study many sources at different ages / conditions - my group’s approach
## Putting it All Together: Measuring Feedback Observationally

Measuring pressures associated with each mechanism

<table>
<thead>
<tr>
<th>Pressure Source</th>
<th>Direct Radiation from stars</th>
</tr>
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<tbody>
<tr>
<td>Relation</td>
<td>$P_{\text{dir}} = u_\nu = \frac{3L_{\text{bol}}}{4\pi r^2 c}$</td>
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<tr>
<td>Methods</td>
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LL+11, LL+14, Olivier+20
Putting it All Together: Measuring Feedback Observationally

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<th>Pressure Source</th>
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<td>( P_x = 2 n_x kT_x )</td>
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<td>Obtain ( n_{\text{HII}} ) using flux density of free-free emission</td>
<td>X-ray spectral modeling of bremsstrahlung</td>
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LL+11, LL+14, Olivier+20
Putting it All Together: Measuring Feedback Observationally

HII Regions in the Magellanic Clouds

Spitzer SAGE, SAGE-SMC Teams

\[ R \sim 3-200 \text{ pc} \]
\[ n \sim 1 \text{ cm}^{-3} \]

Photoionization > Dust-Processed Radiation > Winds/SNe > Direct Radiation

[Graph showing observational data with labels: \( P_\text{dir} \), \( P_{\text{IR}} \), \( P_{\text{HII}} \), \( P_X \)]
Putting it All Together: Measuring Feedback Observationally

Compact HII Regions

- Urquhart+13
  - n > 10^4 cm^-3
  - R < 0.1 pc

Dust-Processed Radiation > Photoionization ~ Direct Radiation (Winds ?)
Putting it All Together: Measuring Feedback Observationally

$$f_{\text{trap}} = 1 + \frac{P_{\text{IR}}}{P_{\text{dir}}}$$ has a median of $\sim 8$

No trend in $f_{\text{trap}}$ with HII region radius < 0.5 pc

$$\dot{E}_{\text{rad}} = f_{\text{trap}} L_{\text{bol}}$$

$$\dot{p}_{\text{rad}} = \frac{\dot{E}_{\text{rad}}}{c}$$

Putting it All Together: Measuring Feedback Observationally

Integral field spectroscopy enables characterization of the stellar content powering HII regions as well as measurement of their gas properties (e.g., density, kinematics)

McLeod+19
Density structure

Velocity structure

Feedback pressures
Future: Measuring Feedback Observationally with SDSS-V

SDSS-V Local Volume Mapper (LVM) will survey the Milky Way, SMC, LMC, M31, and other Local galaxies doing IFS. It will connect small (tens of pc) to large (kpc) scales.

Kollmeier+17  https://www.sdss.org/future/lvm/
**Future: Measuring Feedback Observationally with Lynx**

*Lynx* (successor to *Chandra*) will enable inventories of star clusters and hot gas from feedback.

Detect X-rays from all stars (brown dwarfs up to O/WR stars) out to \( d \sim 5 \) kpc through column densities of \( N_H \sim 10^{23} \) cm\(^{-2}\).
Larger Scales: Galactic Outflows

Galaxy-scale outflows driven by star formation are ubiquitous (Heckman+90, Veilleux+05, Rubin+14)

Prevailing picture is that outflows are driven by hot gas shock-heated by SNe that entrains dust, cold, and warm gases in the flow (e.g., Chevalier & Clegg 85)

Many open questions remain: how does the hot wind couple to the cooler clouds? How does the wind evolve, and how many metals does it carry?

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Lopez+20b
Lopez+20b, arXiv:2006.08623

Temperature and density profiles are broader than expected for adiabatic expansion, suggesting mass-loading / mixing with cooler phase.
Future: Galaxy-Scale Outflows

Conducting a similar analysis for the 15 nearby, edge-on starbursting galaxies.
Future: Galaxy-Scale Outflows

We are turning next to NGC 253. We find that the diffuse X-rays trace the disk’s spiral structure and doing a spatially-resolved analysis now to measure the gradients in temperature/density/metallicity of outflow.

Figure 8: Two-color image of NGC 253, with broad-band (0.5–7.0 keV), diffuse X-rays in blue and Spitzer 8 µm in red. Using 7 × deeper Chandra data than analyzed previously by Strickland et al. (2004), it is apparent that the diffuse X-rays in the disk follow the spiral structure of the galaxy, and the hot (∼10⁷ K) superwind extends several kpc (Lopez et al., in prep). At a distance of d = 3.5 Mpc, 30″ ≈ 0.5 kpc.

I propose to extend this analysis to other nearby (with distances ≲ 30 Mpc) starbursting galaxies which are inclined (i ≳ 60°) so that the outflows are observable in the plane of the sky. Based on archival and literature searches, 15 galaxies meet these criteria and have high-quality X-ray data available. Generally, the observations are much deeper than used in previous studies of the hot gas because the programs focused on the X-ray binary populations, not the diffuse emission. For example, NGC 253 now has 7 × longer Chandra observations than presented in Strickland et al. (2004). The deeper data reveal that the diffuse X-rays trace the spiral structure and extend several kpc perpendicular to the galactic disk (see Figure 8).

As in Lopez et al. (2020b), I will take advantage of the spectro-imaging capabilities of X-ray CCDs to map plasma properties (temperature, densities, and metal abundances) in the starbursts and their outflows. The results will be compared to high-resolution, multi-wavelength data of my collaborators, Drs. Adam Leroy and Alberto Bolatto, to explore the multi-phase nature of the winds. The observational results will be compared to galactic wind models over a wide parameter space to constrain e.g., energy thermalization and mass loading, currently being done by my collaborator Dr. Todd Thompson.

Upon the launch of XRISM (the Hitomi replacement mission; Tashiro et al. 2018) in January 2022, I plan to propose for observations to measure the hot gas velocities as well, providing even stronger constraints on the energy content and mass loading of the hot winds. These high-resolution X-ray spectra will be a powerful new probe of the interplay of hot and cool gas in galaxy outflows (Hodges-Kluck et al., 2019).

III. Impact within the Academic Community

In the last decade, astronomers have begun to appreciate the importance of stellar feedback in star and galaxy formation. In the earliest hydrodynamical simulations, the only feedback mode considered explicitly was SNe, and thanks to better resolution and feedback prescriptions in simulations, astronomers have started to probe the collective effect of the many feedback modes described above. As the predictive power of simulations improves, observational constraints on feedback are sorely needed, and most of the data necessary to produce these constraints are publicly available. My program capitalizes on the substantial past investment of telescope time and resources devoted to studying star-forming regions.

The funding for this proposal will be directed principally toward the support of two graduate students (one Bridge Fellow, see Section IV below, and one PhD student) at OSU. My program is well-suited for the development of a career in astrophysics as it inherently multi-disciplinary and will enable the students to learn to analyze data at many wavelengths. The students will be encouraged to present their research at conferences, to author publications on their work, and to lead observing proposals. Through my collaborators, the students will also have the necessary tools to bridge theory and observations, a valuable skill for independent researchers. On a practical level, they will be able to have multiple letter writers on their behalf when applying for postdoctoral and faculty positions.

IV. Broader Impacts

As a Mexican-American woman, I am deeply committed to enhancing the participation and retention of a diverse workforce in STEM. Throughout my career, I have pursued many avenues toward this goal: organizing formal mentorship activities for students, advising diverse students in research, serving on committees...
Conclusions

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