Calibrating Star Formation Rates on the Galactic Mesoscale

Matthew S. Povich
Assistant Professor, Department of Physics & Astronomy
California State Polytechnic University, Pomona, CA USA
Key Collaborators

**Penn State**
Leisa Townsley
Patrick Broos
Konstantin Getman
Eric Feigelson
Mike Kuhn

**University of Wisconsin**
Edward Churchwell
Barbara Whitney
Marilyn Meade
Brian Babler

**University of Arizona**
John Bieging
Nathan Smith

**University of Exeter**
Tim Naylor

**Cal Poly Pomona**
Alex Rudolph
Remington Sexton*¹
Nicole Sanchez*²
Alec Vinson*³
Anoush Kazarians**

* PhD student
¹ Now at UCR
² Now at Fisk U.
³ Now at UCLA
** Undergrad
Some Definitions

• **Microscale Star Formation**
  - *Few O stars, ONC is most massive cluster.*

• **Macroscale Star Formation** — Extragalactic studies, including starbursts (e.g. Kennicutt 1998, Gao & Solomon 2004, Kennicutt et al. 2009) or parts of galaxies at 0.1-1 kpc scales (e.g. Calzetti et al. 2007, Faesi et al. 2014)

• **Mesoscale Star Formation**
  - Case Study: The Carina Nebula Complex (Povich et al. 2011a,b)
  - Comparative Studies: Chomiuk & Povich (2011), MYStIIX (+ MAGIX?)
The Schmidt-Kennicutt “Law”

Schmidt (1959):
\[ \Sigma_{\text{SFR}} = A \Sigma_{\text{gas}}^N \]

based on observations of stars and gas in the Solar neighborhood.

Kennicutt (1998):
\[ N = 1.4 \pm 0.15 \]

(slope of line fit to data in plot) for a sample of normal, disk galaxies (filled circles, open circles for galaxy centers) and starburst galaxies (squares).
Mesoscale Case Study: The Chandra Carina Complex Project (CCCP)

- Use wide-field, high-resolution, multiwavelength datasets to directly observe the young stellar population of the Great Nebula in Carina and measure its star formation rate (SFR).

- Why Carina?
  - Nearest analog of extragalactic “starburst” regions.
  - Because we’re masochists…

Townsley et al. (2011a) + 15 other papers in an ApJS Special Issue (volume 196)
*Hubble Space Telescope* image of Herbig-Haro jets and pillars in the Carina Nebula
Hubble Space Telescope
~6′ × 12′ mosaic of the
Great Nebula in Carina
Narrow-band visual images by John Gleason, http://jpgleason.zenfolio.com/~2°x2°

D \sim 2.3 \text{ kpc}, 10’ \sim 6.7 \text{ pc.}

Bipolar, proto-superbubble!

The Great Nebula in Carina

- Carina is a “starburst region,” an example of the large-scale star formation seen in starburst galaxies.

- Carina contains at least 200 O and early-B stars, including the prototype O2 I star, +WRs +Eta Car.
~2°x2°

D ~ 2.3 kpc,
10’ ~ 6.7 pc.
Bipolar, proto-
superbubble!

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The *Chandra* Carina Complex Project (CCCP)

- 0.50 – 0.70 keV
- 0.70 – 0.86 keV
- 0.86 – 0.96 keV

Townsley et al. (2011b)
Pre-Main Sequence Stars: Magnetic reconnection flares produce hard (>2 keV) X-rays (e.g. Preibisch et al. 2005).
1439 YSOs, 410 matched to CCCP sources:

- $M > 3.1 \, M_\odot$
- $3.1 > M > 2 \, M_\odot$
- $M < 2 \, M_\odot$

Contours: CCCP stellar density (Feigelson et al. 2011)

Povich et al. (2011b)
YSO Mass Function (YMF)

1439 YSOs detected, incomplete for $m < 3.1 \, M_\odot$

$>20,000$ YSOs predicted, with TOTAL mass $>16,000 \, M_\odot$, extrapolated to $m \geq 0.1 \, M_\odot$

Present-Day SFR: $>0.008 \, M_\odot/yr$

Black curve: Salpeter–Kroupa IMF (Kroupa 2001)
Red curve: Best-fit power law to intermediate-mass YMF (Povich & Whitney 2010; Povich et al. 2011b)
Scaling XLF from 840 stars in the Orion Nebula Cluster (ONC) to match Carina XLFs gives an estimate of total stellar population $>38,000$ diskless PMS stars predicted, extrapolated to $m \geq 0.1 \, M_\odot$.

Povich et al. (2011b)
Carina Nebula SFR from IR and X-ray “Star Counts”

- Global population: $5.8–7.4 \times 10^4$ stars, containing $4.6–5.9 \times 10^4$ $M_\odot$ total mass.

- SFR: $0.009–0.012$ $M_\odot$/yr, averaged over past 5 Myr, punctuated by more intense bursts that created the several massive clusters (e.g. Trumplers 15, 16, and 14).

- Carina Nebula represents $\sim0.5\%$ of the Galactic SFR (Chomiuk & Povich 2011).
What would the Carina H II region look like if viewed from a nearby, external galaxy?
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Extract IR flux densities for Galactic H II regions using large apertures on MSX and IRAS images. Then interpolate their IR SEDs to measure luminosities.

Plot SFR derived from the X-ray + IR “star counts” methods against equivalent Spitzer/MIPS 24 µm luminosity.

*Note the significant, systematic discrepancy between this relation and the Calzetti et al. (2007) extragalactic calibration (dashed line).*

Chomiuk & Povich (2011)
Lada et al. (2012)

Range of CP11 SFRs

x2.7 (again?)
Improving CP11: Nebular SEDs

(A) MYStiX Members

M17
D = 2 kpc

IRAC 8.0 µm
MSX 21 µm
SPIRE 350 µm

(B) PACS
MSX
SPIRE
IRAC

ground based radio

Planck
Improving CP11: Ages on the Probabilistic H–R Diagram (pHRD)

Background

Stars?
Main-sequence
Stars
!

pMAD: Transformation of pHRD into Mass–Age model parameter space

Povich et al. (2014, in prep)

SED modeling of 2376 diskless, X-ray emitting stars from CCCP
1439 YSOs, 410 matched to CCCP sources:

- $M > 3.1 \, M_\odot$
- $3.1 > M > 2 \, M_\odot$
- $M < 2 \, M_\odot$

Contours: CCCP stellar density (Feigelson et al. 2011)
Tr 15 region

Vertical lines (pMADs): subcluster median Age\textsuperscript{j}X (Getman et al. 2014)

Tr 14 region
Tr 16 region

Vertical lines (pMADs): subcluster median Age \( \text{Age}_{\text{X}} \) (Getman et al. 2014)

South Pillars
Massive Young star-forming complex Study in Infrared and X-rays (MYStIX)

- 5-year program, funded by NASA Archival Data Analysis Program (ADAP) and NSF AST grants to Penn State (plus MSP’s NSF Postdoctoral Fellowship award)
- 20 Galactic star-forming complexes, $d = 0.4$ to 3.7 kpc (Feigelson et al. 2013).
- >20,000 X-ray sources + >10,000 IR excess sources classified.

Massive Star-forming regions Across the Galaxy in Infrared and X-rays (MAGIX): Pending NASA ADAP proposal to study 20 of the most massive Galactic complexes (multiple early O stars).
MYStIX: Outer Galaxy “Prototype” Region

NGC 2264
d = 0.9±0.1 kpc

Galactic latitude
Galactic longitude

Stage 0/I YSO
Stage II/III YSO
Ambiguous stage YSO

Povich et al. (2013)
Figure 2. —

- **Serpens South**
  - $d = 0.26$ kpc
  - (not in MYStIX)

- **W40**
  - $d = 0.5$ kpc

- **Lagoon Nebula (M8)**
  - $d = 1.3$ kpc

- **Eagle Nebula (M16)**
  - $d = 1.75$ kpc

- **NGC 6357**
  - $d = 1.7$ kpc

- **4 of the 20 MYStIX Complexes**
  - MIRES Catalog; Povich et al. (2013)
The Bottom Line...

- The combination of X-ray and IR observations of resolved young stellar populations provides a powerful tool for exploring mesoscale star formation the Milky Way.
- We are now in a position to calibrate SFRs versus nebular emission tracers without invoking stellar population synthesis models.
- Goal: bridge the orders-of-mag gulf in scales (spatial, temporal, luminosity) separating the detailed, local studies with extragalactic studies. *Facilitate comparisons of theoretical “universal” SF laws to observations.*