Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy’s Evolution (SAGE) Infrared Stellar Populations

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Collaborators: SAGE Team

http://sage.stsci.edu/
SAGE: Tracing the Lifecycle of Baryonic Matter:

Intermediate mass stars

High mass stars

July 2007

E&F White Conf. on MCs Meixner

credit: http://hea-www.cfa.harvard.edu/CHAMP/EDUCATION/PUBLIC/ICON
SAGE key questions:

- ISM (Bernard): What are the properties and abundance of dust in different parts of the ISM in the LMC?
- Star Formation: What is the galaxy-wide star formation rate of the LMC and how do the details vary on a scale of a few pc?
- Evolved Stars: What is the mass budget of material injected into the ISM by evolved stellar winds?
Why the Large Magellanic Cloud (LMC)?

- Proximity: ~50 kpc (Feast 1999)
- Favorable viewing angle: ~35º (van der Marel & Cioni 2001)
- Mean metallicity ~ ISM during Universe’s peak star formation epoch (z~1.5 Pei et al 1999)
- Known tidal interactions with Milky Way (MW) & Small Magellanic Cloud (SMC)
- Long History of Studies & used as a proving ground:
  ⇒ Ideal Case study for a galaxy’s evolution (Bekki & Chiba 2005)
Spitzer SAGE survey in context of other LMC surveys

Two epochs:
1. Jul/Aug 05
2. Oct/Nov 05

MIPS bands:
24, 70, 160 μm
- Fast Scan map

IRAC bands:
3.6, 4.5, 5.8, 8 μm
- 4 High Dynamic Range images, 12 seconds each.

Bernard & SAGE Team
Meixner et al. (2006)
Previous IR surveys of LMC

- **IRAS**: 12, 25, 60, 100 um (Schwering 1989)
  - 8.5x8.5 degree coverage
  - 1 arc minute angular resolution
  - 1823 object point source list
- **MSX**: 8 um (Egan, van Dyk & Price 2001)
  - 10x10 degree coverage
  - 20'' angular resolution
  - 1806 object point source list
- **2MASS**: J, H, Ks (Nikolaev & Weinberg 2000) & DENIS I, J, H, Ks (Cioni et al. 2000)
  - ~2'' angular resolution
  - 820,000; 1.3 million
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>IRAC Value</th>
<th>MIPS Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Center point</td>
<td>RA(2000): 5h 18m 48s</td>
<td>RA(2000): 5h 18m 48s</td>
</tr>
<tr>
<td>survey area</td>
<td>7.1°×7.1°</td>
<td>7.8°×7.8°</td>
</tr>
<tr>
<td>AOR size, grid size</td>
<td>1.1°×1.1°, 7×7</td>
<td>25′×4°, 19×2</td>
</tr>
<tr>
<td>Total time (hrs)</td>
<td>290.65</td>
<td>216.84</td>
</tr>
<tr>
<td>( \lambda ) (( \mu )m)</td>
<td>3.6, 4.5, 5.8 and 8</td>
<td>24, 70 and 160</td>
</tr>
<tr>
<td>pixel size at ( \lambda )</td>
<td>1.2″, 1.2″, 1.2″, 1.2″</td>
<td>1.2″, 4.8″, 15.6″</td>
</tr>
<tr>
<td>angular resolution at ( \lambda )</td>
<td>1.7″, 1.7″, 1.9″, 2″</td>
<td>5.8″, 17″, 38″</td>
</tr>
<tr>
<td>Exposure time/ pixel at ( \lambda ) (s)</td>
<td>48, 48, 48, 48</td>
<td>60, 30, 9</td>
</tr>
<tr>
<td>Predicted point source sensitivity, 5 ( \sigma ) at ( \lambda ) (mJy)</td>
<td>0.0051, 0.0072, 0.041, 0.044</td>
<td>0.31, 10, 60</td>
</tr>
<tr>
<td>Predicted point source sensitivity, 5 ( \sigma ) at ( \lambda ) (mag.)</td>
<td>19.3, 18.5, 16.1, 15.4</td>
<td>10.9, É, É</td>
</tr>
<tr>
<td>Saturation limits (Jy) at ( \lambda )</td>
<td>1.1, 1.1, 7.4, 4.0</td>
<td>4.1, 23, 3</td>
</tr>
<tr>
<td>Saturation limits (mag) at ( \lambda )</td>
<td>6, 5.5, 3.0, 3.0</td>
<td>0.61, É, É</td>
</tr>
<tr>
<td>Surface brightness limits (Mjy/sr)</td>
<td>É, É, 0.5, 1</td>
<td>1, 5, 10</td>
</tr>
<tr>
<td>Epoch 1</td>
<td>July 15 Š 26, 2005</td>
<td>July 27 Š Aug. 3, 2005</td>
</tr>
<tr>
<td>Epoch 2</td>
<td>Oct. 26 Š Nov. 2, 2005</td>
<td>Nov. 2-9, 2005</td>
</tr>
</tbody>
</table>
7.1° × 7.1°
290 hrs

SAGE IRAC Team:
Whitney,
Meade, Babler,
Indebetouw, Hora &
SAGE team 2006

Meixner et al. 2006
Spitzer Survey of the Large Magellanic Cloud: Surveying the Agents of a Galaxy’s Evolution (SAGE)

http://sage.stsci.edu/

Gordon & SAGE team (Meixner et al. 2006)

IRAC 3.6 μm
IRAC 8.0 μm
MIPS 24 μm
Epoch I Source Counts:
~4.3 million point sources
~650,000 red giant stars
>45,000 dusty evolved stars
>1200 Young Stellar Objects

Diffuse ISM limit
> $1.2 \times 10^{21}$ H/cm$^2$
($A_V = 0.2$ mag)

Indebetouw &
SAGE Team
Meixner et al. (2006)
Table 1: SAGE Epoch 1 Source Lists Release: January 3, 2007
(Meixner et al. 2006, AJ, 132, 2268)

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<td>Epoch 1</td>
<td>July 15 to 26, 2005</td>
<td>July 27 to Aug. 3, 2005</td>
</tr>
<tr>
<td>(\lambda) ((\mu)m)</td>
<td>3.6, 4.5, 5.8 and 8</td>
<td>24</td>
</tr>
<tr>
<td>Epoch 1 point source sensitivity, 5 (\sigma) at (\lambda) (mJy)</td>
<td>0.044, 0.071, 0.45, 0.25</td>
<td>0.5</td>
</tr>
<tr>
<td>Epoch 1 point source sensitivity, 5 (\sigma) at (\lambda) (mag.)</td>
<td>17, 16, 14, 13.5</td>
<td>10.4</td>
</tr>
<tr>
<td>Saturation limits (Jy) at (\lambda)</td>
<td>1.1, 1.1, 7.4, 4.0</td>
<td>4.1, 23, 3</td>
</tr>
<tr>
<td>Saturation limits (mag) at (\lambda)</td>
<td>6, 5.5, 3.0, 3.0</td>
<td>0.60, -3.7, -3.2</td>
</tr>
<tr>
<td>Astrometry (arcseconds)</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Absolute photometry (%)</td>
<td>~5</td>
<td>~5</td>
</tr>
<tr>
<td>SAGEcatalogIRACepoch1 Source counts</td>
<td>~4 million</td>
<td>~60,000</td>
</tr>
<tr>
<td>SAGEcatalogMIPS24epoch1 Source counts</td>
<td>2MASS J, H, K included</td>
<td></td>
</tr>
</tbody>
</table>
Source Populations:

- AGB stars: Blum et al. (2006)
- YSO candidates: Whitney et al.
- PNe: Hora et al. (in prep.)
- Empty field = background galaxies: Whitney, Sewilo et al.

Sewilo & SAGE Team (2006)
contribution of such SF regions to total flux

Indebetouw 2006
SAGE key questions:

- **ISM**: What are the properties and abundance of dust in different parts of the ISM in the LMC?
- **Star Formation**: What is the galaxy-wide star formation rate of the LMC and how do the details vary on a scale of a few pc?
- **Evolved Stars**: What is the mass budget of material injected into the ISM by evolved stellar winds?
Empirical Shell Properties

- Derive Excess by subtracting atmosphere
- Reliable excesses:
  - $5\sigma$ 3.6, and 4.5 $\mu$m
  - $7\sigma$ 5.8 and 8.0 $\mu$m
  - $10\sigma$ 24.0 $\mu$m
- How does this compare to luminosity of star?
  - Power law fits
    - 8.0 $\mu$m : 1.4
    - 24.0 $\mu$m: 1.14

Srinivasan et al. in prep
• AGB, SG
• AGB->O-rich become C-stars during dredge up
• Lower Z, easier to get C/O > 1
• Extreme stars mostly C-rich, but need spectra to decide

Blum et al. (2006)
• Selection of the AGB stars for excess study
• Near-IR (Cioni et al. 2006)
• SAGE colors (Blum et al. 2006)

Srinivasan et al. in prep
• $J-[3.6]$ vs $[3.6]$ CMD (1 in 10 stars shown)

• SAGE has IRAC plus 2MASS catalog, so we can define regions in NIR/MIR CMDs based on Cioni et al.'s split between C- and O- rich stars.

• We further define SG & “Extreme” stars.

Blum et al. (2006)
Distribution of Evolved Stars

- All point sources
- C-rich O-rich AGB stars
- Supergiants Extreme AGBs
- Other
24 microns

- Normal stars compressed further
- SG/L-AGB have larger excess than E stars
- See lower L mass losing sources -> cool, dusty envelopes
- IRS sources cover brightest population

Blum et al. (2006)
Empirical Shell Properties

Determine a best fit model atmosphere to “bluest”, i.e. without excess, stellar photometry

Srinivasan et al. in prep
Empirical Shell Properties

- Derive Excess by subtracting atmosphere
- Reliable excesses:
  - $5\sigma$ 3.6, and $4.5 \mu m$
  - $7\sigma$ 5.8 and $8.0 \mu m$
  - $10\sigma$ 24.0 $\mu m$
- How does this compare to luminosity of star?

Power law fits
- $8.0 \mu m : 0.87$
- $24.0 \mu m : 1.22$

Srinivasan et al. in prep
• Flux at these wavelengths assumed to be excess
• How does this compare to luminosity of star?
  Power law fits
  - 8.0 μm : 1.5
  - 24.0 μm: 2.3
• Color temp derived from ratio of 8 to 24 μm fluxes.
• How does this compare to excess dust emission?
• No trend for O and C rich
• Decrease for extreme:
  \[ T(K) = 728.8 \times \text{Ex}_{24}^{-1.7} \]
• Assume color temp, derive opacity at 24 $\mu$m from flux.
• How does this compare to excess dust emission?
• Clear trend: excess increase is related to optical depth (mass-loss rate)
• $\tau_{24} = 0.0186 \times \text{Ex}_{24}^{1.32}$

Empirical Shell Properties

Srinivasan et al.
Evolved stars Model Grid

Kevin Volk
Variable Stars

- Variables identified in two SAGE Epochs
- Variability index > 3 in IRAC bands
- Multiband criteria
- Find candidate young stars too

Uma Vijh
Variable SEDs

O-rich AGB

C-rich AGB

Extreme AGB

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Evolved star variables
Locations on 3.6 micron image

Vijh 2007
Planetary Nebulae: Hora et al. in prep.
233 known PN, 186 with IRAC detections, 170 with MIPS 24
Planetary Nebulae: Hora et al. in prep.

Galactic PN, LMC PN
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IRAC+MIPS color-mag, 50 kpc

- Stage I
- Stage II
- Stage III

Sustained star formation for 2 million yrs with Kroupa IMF
IRAC+MIPS color-mag, 50 kpc

- $M_{\text{star}}/M_{\odot} < 2$
- $2 < M_{\text{star}}/M_{\odot} < 8$
- $M_{\text{star}}/M_{\odot} > 8$
point sources ~ candidate YSOs/protoclusters

Whitney, Indebetouw et al. 2007 in prep.
point sources ~ candidate YSOs/protoclusters

Whitney, Indebetouw et al. 2007 in prep.

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YSOs: where?

candidate YSOs: where?

Whitney, et al., Sewilo, Indebetouw et al.,
candidate YSOs: where?

Whitney, Sewilo, Indebetouw et al.,
Whitney et al. in prep.
Star formation rate: $0.1 \, M_\odot / yr$

YSO Mass function: Kroupa IMF,
Luminosity function
Is there an embedded star formation region in the southern cloud?

(Indebetouw et al. in prep.)
Star formation in southern cloud has a low level of activity.

YSO models: \(2 \times 10^4\) M\(_{\text{sun}}\) in stars, \(10^6\) M\(_{\text{sun}}\) in gas.

H-alpha (Schmitt-Kennicutt): \(3.4 \times 10^4\) M\(_{\text{sun}}\) in stars too high.

H-alpha & 24 um (Calzetti 2007): 1300 M\(_{\text{sun}}\) in stars too low.

Indebetouw et al.

2MASS J, H, K

IRAC 3.6, 4.5, 8

MIPS 24, 70, 160
Summary

• Be Green: think Recycling, not just consumption (i.e. star formation)
• ISM: Compared to MW:
  • 3.3 times less dust in the LMC than in MW
  • ~3.7 times less dust per H in CO than in HI: XCO factor issue
• Star Formation:
  • >1000 new YSO candidates uncovered,
    • spatial distribution correlates with ISM gas
    • Criteria biased towards massive star range, 1-50 $M_\odot$
  • Star formation rate 0.1 $M_\odot/yr$
• Evolved stars:
  • Populations identified: supergiants, O-rich, C-rich & extreme AGBs
  • Infrared excess emission increases with AGB star luminosity
    • Trend caused mostly by optical depth, i.e. Mass loss rate
SAGE as a Legacy

- SAGE will trace the lifecycle of baryonic matter in the LMC by observing dust emission
- Original pipeline data released immediately
- Point source catalogs to be provided:
  - Epoch 1 release, Jan. 3 at IRSA: http://irsa.ipac.caltech.edu
  - Next year: Epoch 2 and mosaicked photometry
- Improved mosaiced images provided: next year
- http://sage.stsci.edu/
- Future: SAGE-SMC (PI: Gordon), SAGE-Spec (co-PI’s Marwick-Kemper & Tielens).

Meixner & SAGE Team (2006)
SAGE team members: http://sage.stsci.edu/

- **Space Telescope Science Institute:** Meixner (PI, database lead), Leitherer (team web page), Vijh Nota, Panagia, Smith, Shiao, Sewilo
- **University of Wisconsin:** Meade, Babler, Churchwell, Gallagher
- **SSI:** Whitney (IRAC pipeline lead, star formation co-lead)
- **University of Arizona:** Gordon (MIPS pipeline lead), Engelbracht, Misselt, For, Zaritsky, Harris, Kelly, Perez
- **Spitzer Science Center/JPL:** Reach (ISM co-lead), Latter, van Dyk, Werner, Gorjian
- **NOAO/CTIO&Tucson:** Blum (Evolved star lead), Olsen, Mould, Points
- **Nagoya University, Japan:** Onishi, Fukui, Kawamura, Mizuno, Mizuno (CO survey), Shibai (ASTRO-F), Shuji (Near-IR survey)
- **CESR/Saclay/IAS:** Bernard (ISM co-lead), Madden, Boulanger, Paladin
- **UC Berkeley:** Cohen (calibration)
- **University of Virginia:** Indebetouw (star formation co-lead), Kemper (IRS)
- **Harvard/CfA:** Hora (IRAC team)
- **NASA/Ames:** Tielens (IRS)
- **University of Denver:** Ueta
- **Gemini:** Volk
- **University of Michigan:** Oey
- **AURA:** Frogel
- **CSIRO:** Staveley-Smith
The SAGE Team:
http://sage.stsci.edu/
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Backup slides
global analysis

SF in galaxies courtesy D. Calzetti (Calzetti et al. 2007, Kennicutt et al. 2007):

HII regions, entire starbursts, LIRGs

Gordon et al. 2007 in prep.
Whitney et al. in prep.
Whitney et al. in prep.
Classification

- Cioni et al. (2006) use Marigo models to explain C-star locus in 2MASS CMD
- Define photometric selection of C-, M- stars

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