Triggered star formation, HII regions and *Spitzer* bubbles

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Outline of the lectures

1. Observational surveys for infrared bubbles
   • *Spitzer* bubbles & the Milky Way Project

2. Theory of bubble formation & triggered star formation
   • HII regions & wind-blown bubbles
   • Collect & Collapse and Radiative-Driven Implosion

3. The star-forming environment of bubbles & HII regions
   • Sequential star formation
   • Statistical studies
Triggered star formation around bubbles?


The environment shows that there is associated SF (6.7 GHz methanol masers, IR sources, sub-mm clumps)

However, these sorts of studies are phenomenological

(Identifying “triggered” star formation visually in environments where it’s likely to happen)
Star formation at the edges of HII regions

W5 HII region
Bright rimmed clouds

Photoionised clouds/clumps
Bright rim of ionised gas
Striations reveal photoevaporative flow
Forming small clusters of stars

H-alpha NOT images
Bright rimmed clouds


Most clouds have properties consistent with Radiative Driven Implosion models

Free-free emission from ionised boundary layer

Associated with sub-mm cores, embedded IR sources. Suggestion of higher IR luminosities → may be forming clusters/higher mass stars

Leflocq & Lazareff 1997
Is the star formation triggered?

Clear morphological evidence that these clouds are being photoionised
Recent star formation identified in several clouds (Thompson... Urquhart... Morgan...)
But large inaccuracies in dating the passage of the shock front and the epoch of star formation mean that the evidence is mostly inconclusive.

(Urquhart et al 2007)

SFO 75
The Origin Problem

To prove that a star or YSO was triggered we have to prove that it would not have formed without an external force.

Proving a negative is difficult!

The origin problem - we can’t point to a single SF region and say it how it formed.

“Show me what a triggered star forming region looks like! Is that one? How about that one?” Mark Krumholz, Townsville SF meeting

“Dense molecular shells and pillars around HII regions often do have such triggering, although sometimes it is difficult to see what is triggered and what stars formed in the gas before the pressure disturbances.” Elmegreen 2011
Sequential star formation

Can observe age sequence of stars along the direction of the photoionisation shock

Young star towards the centre of the BRC, older stars closer to the HII region.

Small scale sequential star formation (Sugitani et al 1995)

Reach et al (2009) - class II YSOs dispersed, class I/0 objects concentrated towards head of Elephant Trunk Nebula

Hayashi et al (2012) - class I YSOs concentrated towards head of BRCs

Ikeda et al 2008
Sequential star formation

Getman et al (2012)

X-ray/optical selected sample of stars & YSOs

Date stars by FLWO optical spectra

Clear age gradient seen towards Elephant Trunk
Sequential star formation from WISE

WISE-selected YSO sample in W5 & other regions (Koenig et al 2012)

$r^{-1}$ surface density of YSOs implies smooth outward progression of SF

Koenig et al argue this is not consistent with Collect & Collapse

But also note that WISE is not sensitive to YSOs without disks & subject to field source contamination
Statistical studies of Spitzer bubbles

When you can’t do things on an individual basis, turn to statistics!

Simple geometry of Spitzer bubbles lends itself nicely to investigation of the amount of SF as a function of distance from the bubble centre.

Two studies so far:


Kendrew et al (2012) - based on the Milky Way Project bubbles

Both studies use the uniform and comprehensive Red MSX Source (RMS) survey to trace Massive Young Stellar Objects (Urquhart et al 2010).
The Red MSX Source Survey

Comprehensive project to identify well-selected uniform sample of MYSOs from MSX survey

Initial colour selection from Lumsden+ (2002) then comprehensive multi-wavelength follow-up to reject non-YSOs (Urquhart+ 2007-2012)

Resulting sample has well constrained distances, luminosities (Mottram+ 2011)

Population modelling sets limits on accretion history (Davies+ 2011) - consistent with turbulent core & competitive accretion models
Statistical studies of Spitzer bubbles

Thompson et al (2012):

We use the Churchwell et al 2006 bubble catalogue: 322 bubbles in the GLIMPSE I survey area.

Select objects from the RMS catalogue with YSO and UC HII classifications: 850 “YSO” in the GLIMPSE I region.
The surface density of YSOs

Plot surface density of RMS “YSO” against fractional bubble radius (i.e. scaled by mean angular radius of bubble)

RMS “YSO” are clearly associated with *Spitzer* bubbles!

Significant peak in distribution at a radius equivalent to 1 bubble radius

Beyond 2 bubble radii the surface density of RMS “YSO” drops to a constant background level
The surface density of YSOs

Same result for an independently selected catalogue of “Intrinsically Red Objects” (Robitaille et al 2008)

Broader peak - but IRO are not selected in the same way as RMS

Again, significant peak in distribution at a radius equivalent to 1 bubble radius

Beyond 2 bubble radii the surface density of IRO drops to a constant background level - higher than RMS, but many more IRO in the catalogue.
The surface density of YSOs


Completely independent radio selection technique for massive YSOs

Again, significant peak in distribution at a radius equivalent to 1 bubble radius

Result not as significant - but most MMB masers in the southern Galactic Plane so bubble sample is reduced by ~ factor 2
An overdensity of YSOs around bubbles

Take a distance of 2 bubble radii as a yardstick for association

< 2 bubble radii the mean surface density is $8.9 \pm 1.7$ “YSO”s per unit area

> 2 bubble radii the mean surface density is $3.1 \pm 0.2$ “YSO”s per unit area

Two sample unequal variance t-test yields a 0.4% probability that these means are drawn from the same sample.

Overdensity of “YSOs” around bubbles significant at the 3σ level.

Peak at radius of 1 significant at 4σ
The angular cross-correlation function

The two-point angular cross-correlation, $\omega(\theta)$, measures the probability of finding one population of objects at a certain angular distance from another population.

We use a modified version of the Landy & Szalay (1993) estimator from Bradshaw et al (2011):

$$\omega(\theta) = \frac{N_{D_1D_2} - N_{D_1R_2} - N_{R_1D_2} + N_{R_1R_2}}{N_{R_1R_2}}$$

N... represent normalised number counts of data-data, data-random, random-random angular distance pairs. Distance pairs expressed in fractional bubble radii.

Random samples chosen to have similar latitude distributions.

50 Random samples used to avoid introducing too much noise.

Errors $\omega(\theta)$ in calculated by bootstrapping 100 random subsamples. Estimator has close to Poisson noise, but not precisely.
Angular cross-correlation shows that the RMS “YSO”s are strongly correlated with the bubbles.

Bubble-”YSO” correlation peaks at a bubble radius of 1 with a 9σ significance.

Correlation decreases to essentially zero by a bubble radius of 2.

Consistent with the surface density results.

Strong evidence of an overdensity of “YSO”s with the bubbles, with higher probability of finding a “YSO” coincident with the rim of a bubble.
Out of 322 bubbles we find 72 associated with RMS “YSO”s

Out of 846 “YSOs” we find 116 within 2 bubble radii of a bubble

Bubbles associated with RMS “YSO”s are in general smaller and with thinner rims than bubbles that are not

Mean radius of “YSO” bubbles: $3.4' \pm 0.4'$ vs non-”YSO” bubbles: $4.6' \pm 0.3'$

Mean thickness of “YSO” bubbles: $0.92' \pm 0.08'$ vs non-”YSO”: $1.18' \pm 0.07'$

Note that t-tests reveal these means differ by only 99% & 99.2% probability respectively - not highly significant - also these are the angular sizes not spatial!

But smaller & thinner bubbles ought to be younger (Weaver et al 1977, Dale et al 2009) - hence suggests that SF is associated with younger bubbles.
The luminosity function of triggered SF?

Some suggestion that triggered SF results in stars with higher luminosity than spontaneous SF.

Can test this by making a luminosity function of YSOs associated with the bubbles compared to all the RMS YSOs.

K-S test of the luminosity distributions yields a not significant probability that the two are drawn from different population.

Also, 116 out of 846 RMS “YSO”s are associated with bubbles. If they are triggered this suggests a lower limit for the fraction of triggered massive SF of 14%.
Kendrew et al (2012) repeated the same study on the MWP bubbles.

In the larger sample the overdensity at the rim disappears...

But, the RMS YSOs are now drowned by bubbles (only ~ 0.2 YSOs per bubble)

Monte Carlo tests show that as the YSO/bubble ratio decreases, an artificially injected signal disappears

(Kendrew et al 2012)
The 3rd dimension

GLIMPSE 8 \(\mu m\) image of \(l=320.5\)

2 MWP bubbles (many more not shown)
The 3rd dimension

GLIMPSE 8 µm image of l=320.5

2 MWP bubbles (many more not shown)

RMS YSOs/UC HII
The 3rd dimension

GLIMPSE 8 μm image of l=320.5

2 MWP bubbles (many more not shown)

RMS YSOs/UC HII with $V_{lsr}$

Spot the interloper!
Take the yardstick of association as 2 bubble radii as in Thompson et al 2012

72% of these bubbles are associated with YSOs with <10 km/s spread

28% of MWP bubbles are associated with YSOs spread by > 10 km/s

Some are “associated” with YSOs that are up to 90 km/s apart

Clearly these “associations” are not single complexes...
Sample selection 1: limited $V_{\text{LSR}}$ spread

Select all large bubbles with $>1$ RMS YSO within 2 bubble radii

Now select out those bubbles where the absolute velocity difference of the YSOs is $< 10$ km/s

Surface density shows a peak just outside 1 bubble radius
Sample selection 2: high hit rate

Select all large bubbles with hit rate > 0.4

This results in a comparable sized sample to Churchwell et al 2006

Again, a centrally peaked distribution

Surface density shows a secondary peak at 1 bubble radius
Next steps: velocities

We need to know the velocity of each bubble so we can identify nearby star formation

CO measurements:
- Galactic Ring Survey
- JCMT 13CO/C18O
- NANTEN2 GPS!

Radio Recombination lines:
- GBT HII Region Discovery Survey
- THOR VLA survey
- MeerGAL MeerKAT survey
Next steps: better YSO catalogues

The Herschel Hi-GAL Galactic Plane survey (Molinari et al 2010)

Will allow multiwavelength selection of YSOs much fainter than in the RMS catalogue around all the bubbles in the GLIMPSE survey.

Also Herschel HOBYS project, which includes a number of potentially triggered regions
Summary

Lots of star formation observed at edges of HII regions and bubbles

Difficult to prove that it is triggered - the origin problem

Look for age gradients - sequential star formation

Can use statistical methods

Triggered star formation may be important contribution to Galactic SFR

Plenty of work still to do!!

(Better models with more physics, velocities, YSO surveys...)

High abundances of $^{26}$Al and $^{60}$Fe found in asteroid chondrules - injected by SNe & stellar winds

Consistent with the Collect & Collapse model

Gounelle & Meynet (2012)