Triggered Star Formation and Young Stellar Population in Bright-Rimmed Clouds

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Influence of massive stars on subsequent star formation

Outline

1. Introduction
2. Observation & Data Reduction
3. Results & Analysis
4. Conclusion

Bright-Rimmed Clouds

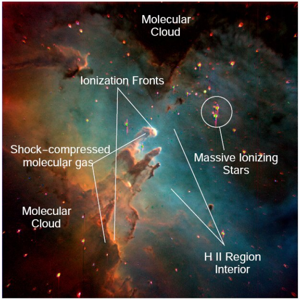
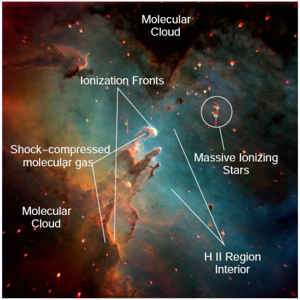


Figure 2. The structure of a blister H II region. This is a ground-based image of the Eagle Nebula, M16, obtained with the 1.5-m telescope at Palomar Observatory.

Hester & Desch (2005)

- Location: found at the borders of HII regions
- Morphology: bright-rim facing the ionizing sources and a tail along the radially outward direction from the central stars
- Propagation of ionization/shock fronts, produced by massive stars, into the surrounding molecular material compress the gas which lead to the formation of dense cores
- Cores subsequently collapse to form a new generation of stars

Bright-Rimmed Clouds



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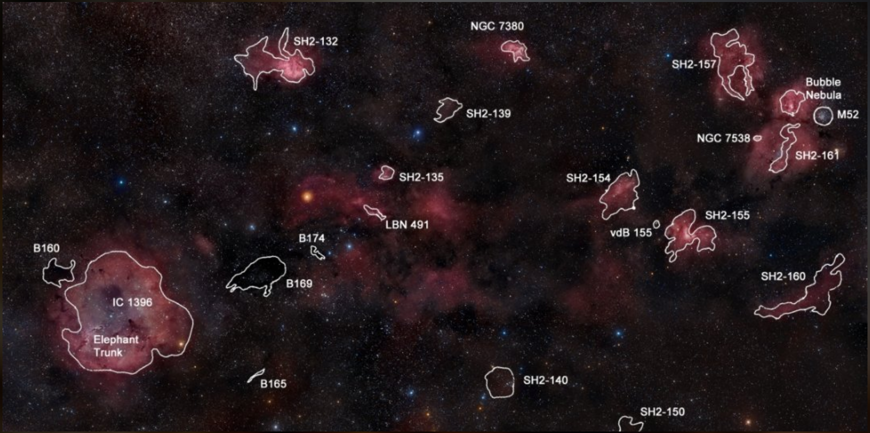
- Cores subsequently collapse to form a new generation of stars
- Observational evidence: `sequential star formation`

Cepheus: IC 1396: SFO 38



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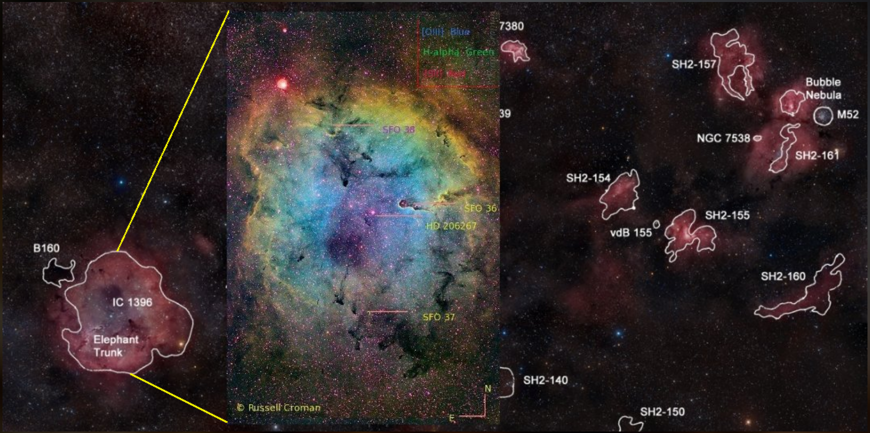

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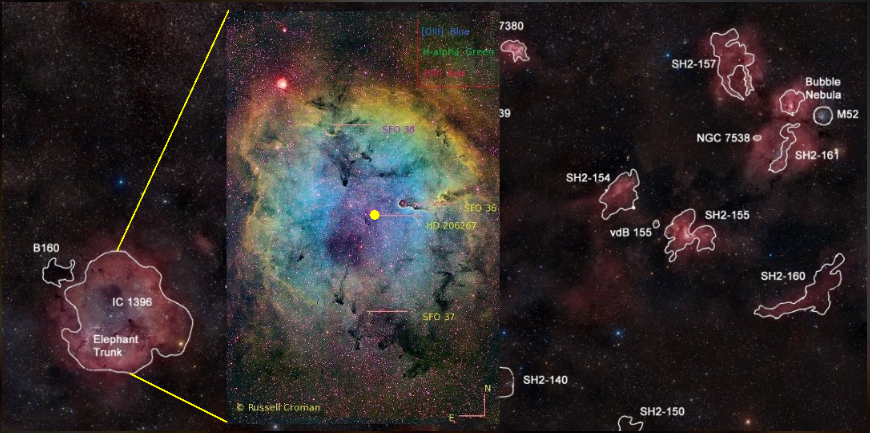

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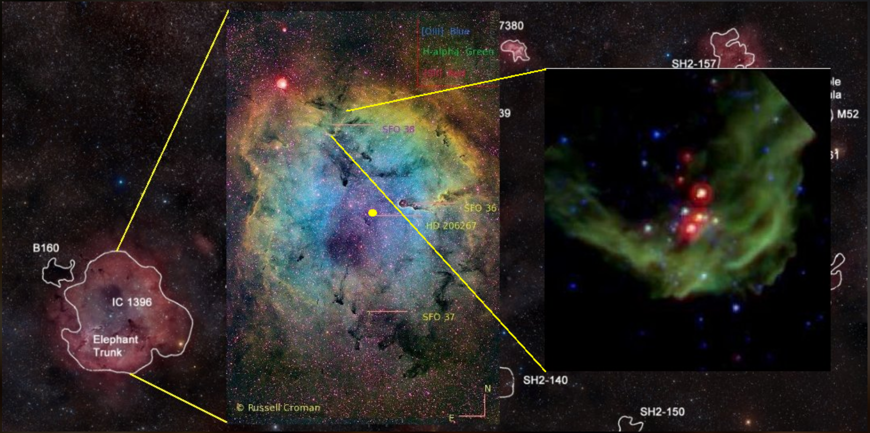

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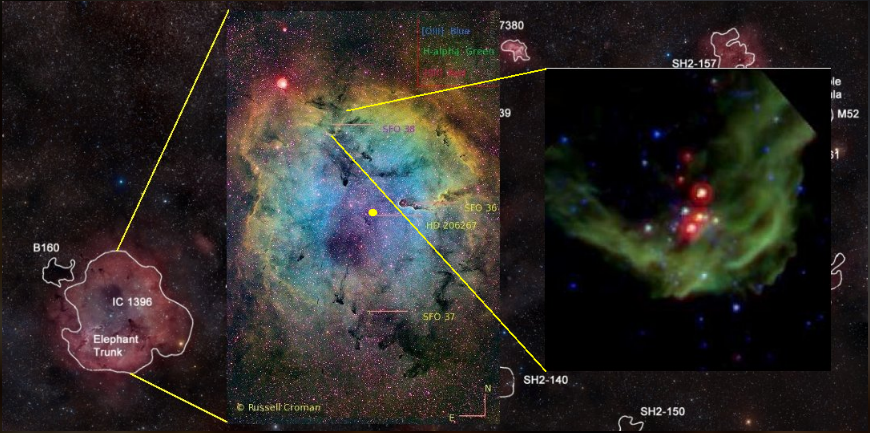

Signatures of ongoing star formation: luminous IRAS source IRAS 21391+5802, H_2O maser sources, molecular outflows, HH outflows, NIR embedded clusters, Hα emission line stars ...(Kun et al., 2008)

Observations & Data Reduction

Observations & Data Reduction

- IRAC (3.6, 4.5, 5.8, and 8 μm) and MIPS (24 μm) observations were retrieved from the *Spitzer Space Observatory* archive (Program ID 30050: Fazio et al.)
- Spitzer Mopex and custom IDL routines

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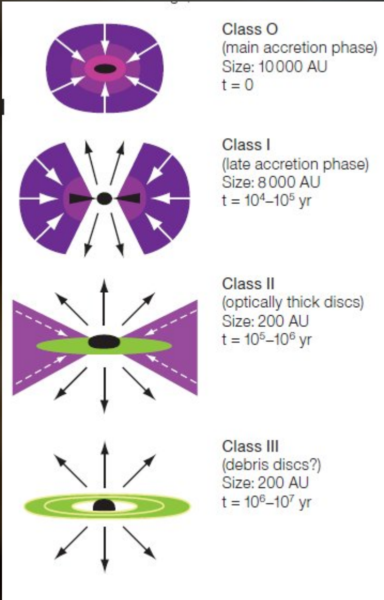
http://www.iiap.res.in/centers/iao

- Optical photometric and spectroscopic observations were obtained using *HFOSC* instrument mounted on 2m Himalayan Chandra Telescope, Hanle, India
- IRAF and custom IDL routines

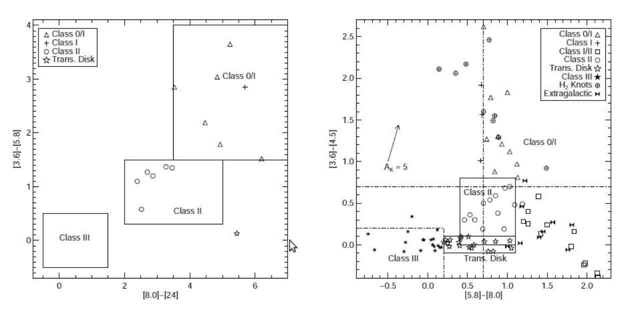
Results & Analysis

Classification of YSOs



Classification of YSOs

- IRAC and MIPS color-color diagrams are used to *identify* and characterize the *evolutionary stages* of YSOs



Fang et al. (2009) Gutermuth et al. (2009) Hartmann et al. (2005) Megeath et al. (2004) Muzerolle et al. (2004)

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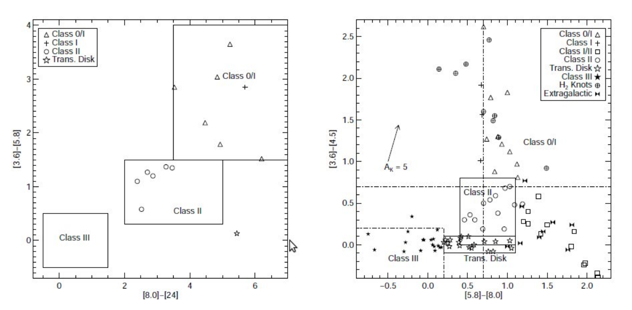


Total MIR sources: 110

Class 0/I: 10

Class I: 3

Class I/II: 13

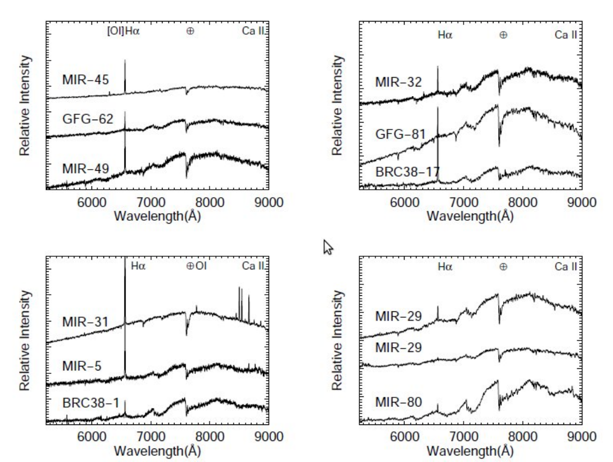
Class II: 14

Transitional disk objects: 19

Fang et al. (2009) Gutermuth et al. (2009) Hartmann et al. (2005) Megeath et al. (2004) Muzerolle et al. (2004)

Spectroscopy of YSOs

- Medium resolution ($\sim$ 7Å) spectra were obtained for relatively bright and optically visible YSOs



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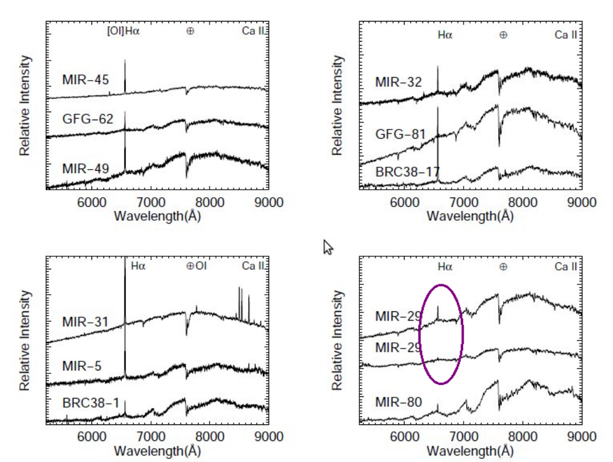


Spectral Classification

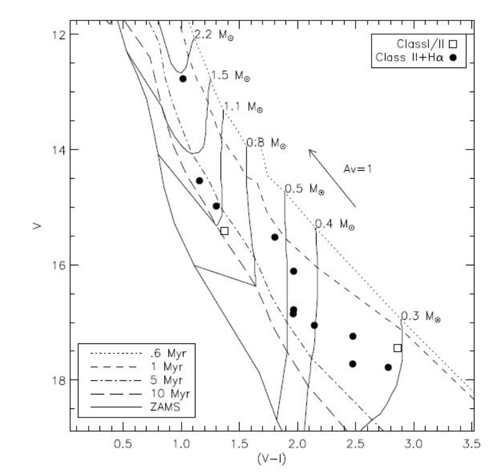
- Spectra were classified using a modified version of *SPTCLASS* code (Hernández et al. 2004) optimized for *HFOSC* spectra

- Full width of the Hα emission line at 10% of the peak intensity (Hα [10%]) $>$ 270 km s^{-}1 $\Rightarrow$ accreting CTTS (White & Basri 2003)

ID	Alt. ID	Date (dd/mm/yy)	W_{λ} (Å)	Sp. Type (±subtype)	$T_{\rm eff}$ (K)	Type	Hα[10%] (km s^{-1})	log $\dot{M}_{ac}$ ($M_{\odot}$ yr^{-1})
BRC 38 1		05/10/08	−12.93	M3 ± 1	3470	CTTS	312.23	−9.86
		10/10/09	−16.24				205.29	−10.90
MIR-5	BRC 38 2	05/10/08	−85.23	M1 ± 1	3720	CTTS	359.79	−9.40
		10/10/09	−106.1				244.53	−10.52
MIR-7	BRC 38 3	06/10/08	−19.0	M1 ± 2	3720	CTTS	476.25	−8.27
		10/10/09	−18.75				463.50	−8.39
MIR-11	BRC 38 4	10/09/08	−7.30	M1 ± 2	3720	WTTS		
		18/07/09	−11.29					
MIR-29	BRC 38 5	06/09/08	−3.42	M1 ± 2	3720	WTTS		
		03/11/08	−8.84				469.90	−8.33
		24/08/09	−1.89					
		09/11/09	−2.74					
MIR-31	BRC 38 6	06/09/08	−53.47	K2 ± 1	4900	CTTS	384.43	−9.16
		24/08/09	−57.32				442.02	−8.60
		09/10/09	−60.5				382.26	−9.18
MIR-32	BRC 38 7	10/09/08	−33.12	M2 ± 1	3580	CTTS	368.03	−9.32
		12/09/09	−15.78				220.59	−10.75
MIR-43	GFG 62	18/07/09	−3.516	M1 ± 1	3720	WTTS		
MIR-45	BRC 38 9	06/09/08	−37.43	K4 ± 1	4590	CTTS	281.09	−10.16
		03/11/08	−41.22				389.74	−9.11
		24/08/09	−56.33				273.39	−10.24
MIR-49	BRC 38 10	04/11/08	−13.5	M0 ± 1	3850	CTTS	430.70	−8.71
		09/10/09	−30				450.55	−8.52
MIR-64	BRC 38 11	10/09/08	−31.46	K5 ± 1	4350	CTTS	239.20	−10.57
		12/09/09	−25.06					
MIR-76	GFG 81	18/07/09	−3.261	K7 ± 1	4060	WTTS		
		10/10/09	−3.135					
MIR-80	BRC 38 12	24/08/09	−8.404	M4 ± 1	3370	WTTS		
BRC 38 17		11/11/09	−119.	M3 ± 2	3470	CTTS	205.29	−10.90

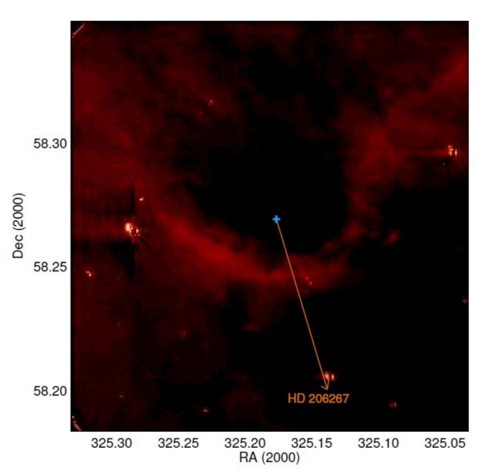
- Mass accretion rate (log$\dot{\rm M}_{ac}$) =- 12.89 ($\pm$0.3) + 9.7 ($\pm$0.7) $\times$ 10^{-3} Hα [10%] (Natta et al. 2004).

Optical Colour-Magnitude Diagram



- Isochrones from Siess et al. (2000) assuming a distance of 750 pc (Matthews 1979)
- Ages: 1 to 5 Myr and masses: 0.3 to 2.2 $M_\odot$ for Class II YSOs [with(out) Hα]

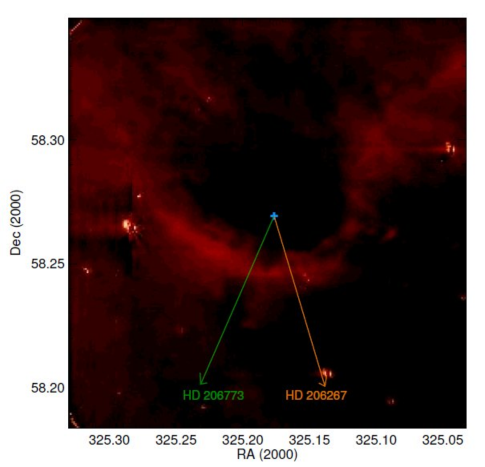
Hα Emission: SFO 38



Choudhury et al. (2010)

- The bright-rim structure is quite prominent in the continuum-subtracted Hα line image
- Hα emission line image is asymmetric w.r.t. HD 206267

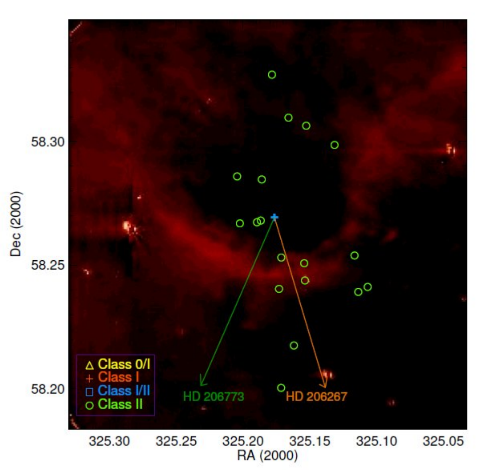
Hα Emission: SFO 38



Choudhury et al. (2010)

- HD 206773 a B0V type star at a projected distance of 7.6 pc
- Strongren radius of a BOV type star would be $\simeq$ 8.5 pc assuming $n_H \sim 10^7$ m$^-3$
- HD 206773 could be another potential ionizing source for SFO 38

Spatial Distribution of YSOs in SFO 38



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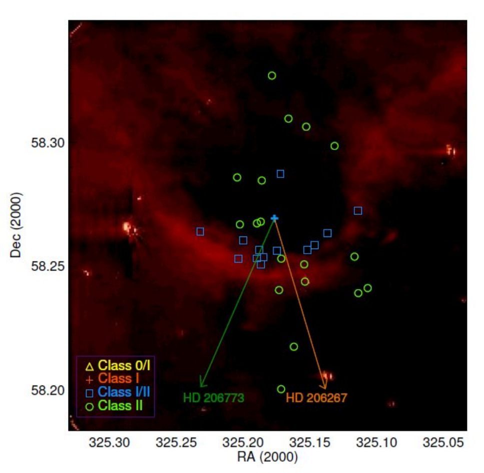

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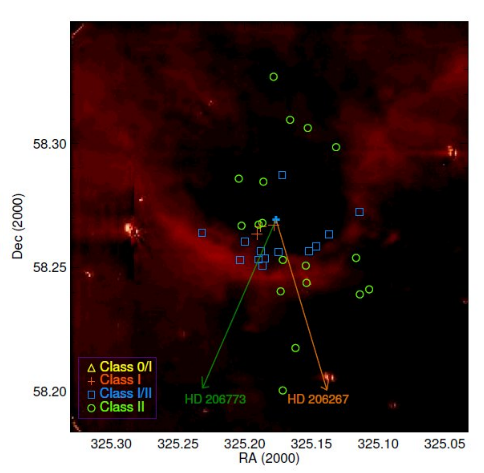

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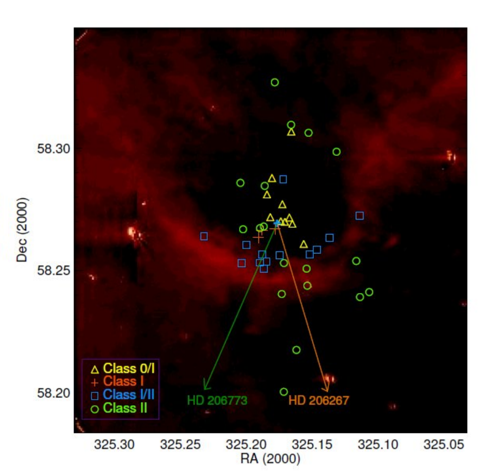

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- Class I/II and Class I YSOs are situated behind the rim
- Class 0/I YSOs are situated at the dense core

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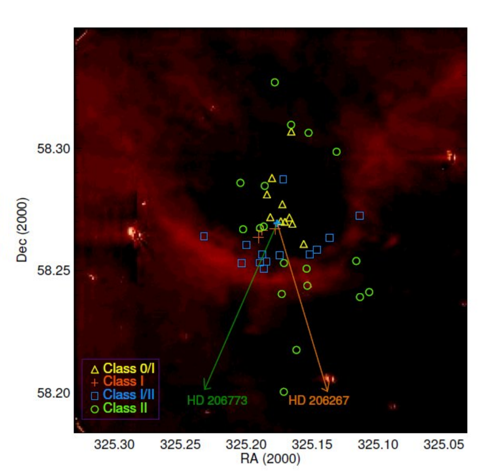

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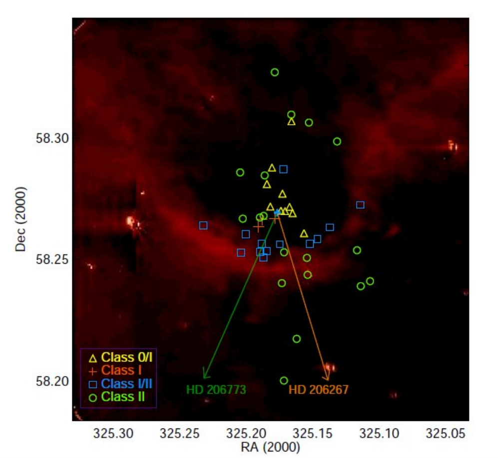
- A spatio-temporal gradient along the directions of both HD 206267 and HD 206773

The Protostellar Cluster at IRAS 21391+5802

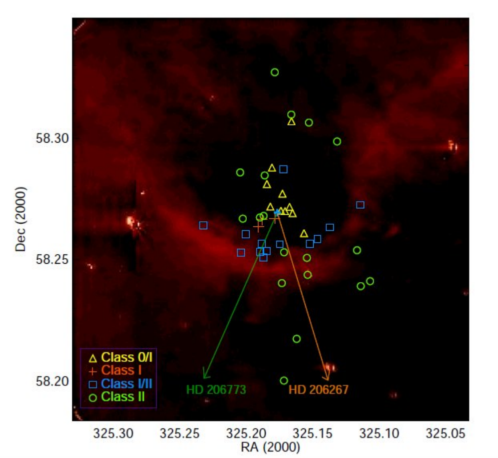


Choudhury et al. (2010)

SED fitting tool: Robitaille et al. (2007)

- IRAS 21391+5802 in SFO 38 can be resolved into three components, named as BIMA 1, BIMA 2, and BIMA 3 (Beltrán et al. 2002)
- MIR-50 and 54 are identified as the mid-infrared counter-parts of BIMA 2 and BIMA 3
- MIR-50 (BIMA 2) is a Class 0/I intermediate-mass YSO with mass of 5.97 M$_\odot$. Neri et al. (2007) have shown BIMA 2 as having three com-ponents
- MIR-54 is a Class 0/I low-mass YSO with mass of 1.5 M$_\odot$.
- The SED models derive the age of both these sources to be $\sim 10^5$ yr

Triggered Star Formation in SFO 38



Choudhury et al. (2010)

- Triggered or influenced star formation by the massive stars?

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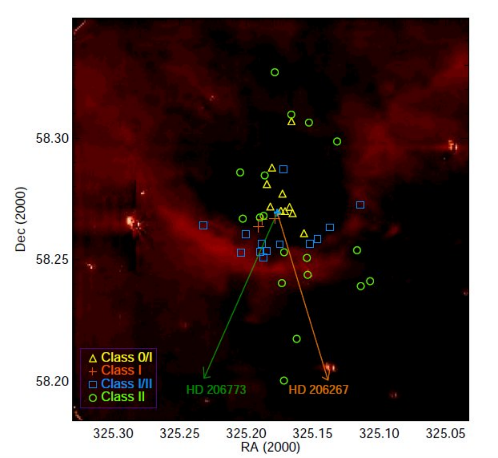
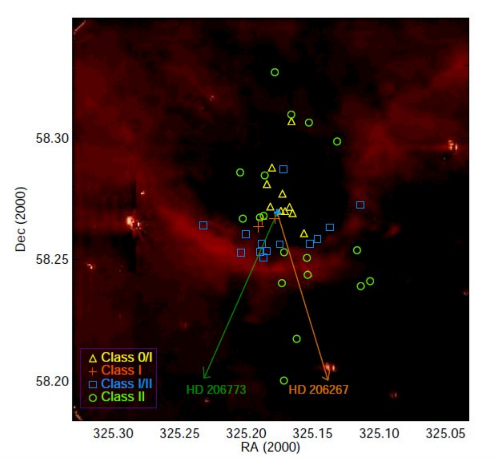


Choudhury et al. (2010)

- Triggered or influenced star formation by the massive stars?
- UV radiation merely exposes the young stars formed inside the globule by photoevaporation
- The observed evolutionary sequence of YSOs is due to the modification of the protoplanetory disks of YSOs by the intense UV radiation

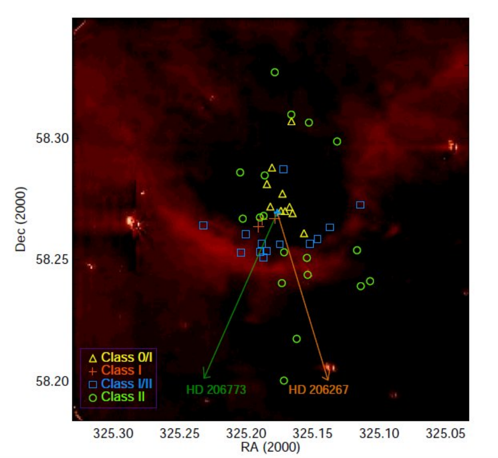
Triggered Star Formation in SFO 38



Choudhury et al. (2010)

- Elongated distribution of YSO along two different axes from the bright-rim to the dense core
- Typical radius of influence of O-type stars is found to be $<$1 pc (Balog et al. 2007; Hernández et al. 2008). The mean projected distance of SFO 38 from the nearby OB-type star is $\sim$9pc
- Spatial distribution of YSOs in SFO 38 signifies the temporal evolution $\Rightarrow$ observational evidence for sequential star formation

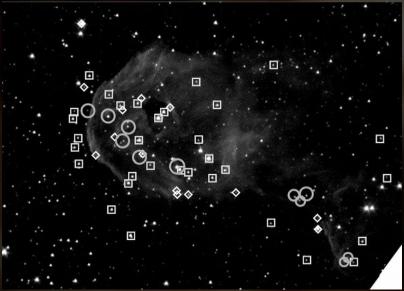
Triggered Star Formation in SFO 38



Choudhury et al. (2010)

- Temporal feasibility of shock waves propagation
- Shock propagation speed : 0.1-0.3 km s^{-1} is consistent with the values obtained from numerical simulation (Miao et al. 2006)

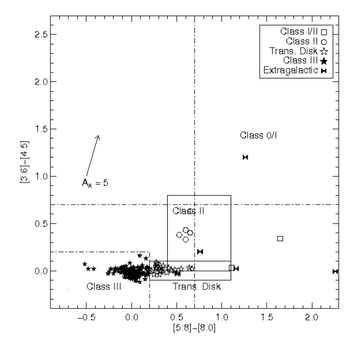
Spatial Distribution of YSOs in SFO 36 and SFO 37



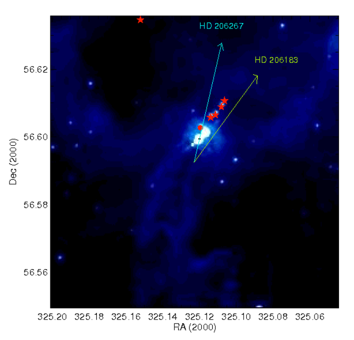
SFO 36: Sicilia-Aguilar et al. (2006)

SFO 37: Ikeda et al. (2008)

Spitzer View of Star Formation in SFO 37



IRAC Color-Color Diagram



Spatial distribution of YSOs in SFO 37

Choudhury et al., 2010a, (in preparation)

Conclusion

- Star formation in SFO 38 have been triggered by massive OB-type stars
- Low to intermediate mass YSOs are formed in SFO 38
- Spatio-temporal gradient in the spatial distribution of YSOs advocate for sequential star formation

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Thank You