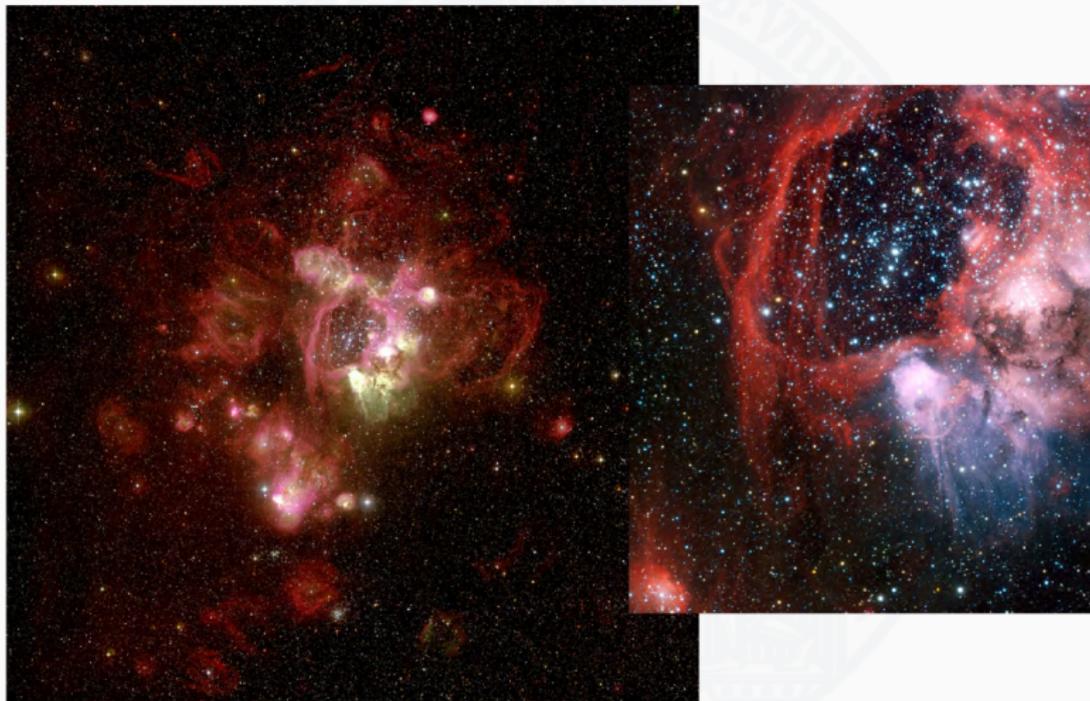


LHA-120 N44 in the Large Magellanic Cloud



MPG/ESO 2.2-m WFI (Credit: *Comerón, Delmotte & Laval*)

Hay 3 mecanismos propuestos:

1 **Collect and Collapse (CC):**

- Propuesto por Elmegreen & Lada (1977)
- Frente de choque 'colecta' gas y polvo y se forma una cáscara densa en expansión.
- Con el tiempo se inestabiliza y se fragmenta formando núcleos densos que 'colapsan' y se forman estrellas.
- Formulación analítica: Whitworth et al. (1994): densidad uniforme - cáscara esférica en expansión: estima parámetros de tamaños, masas, tiempos de fragmentación.

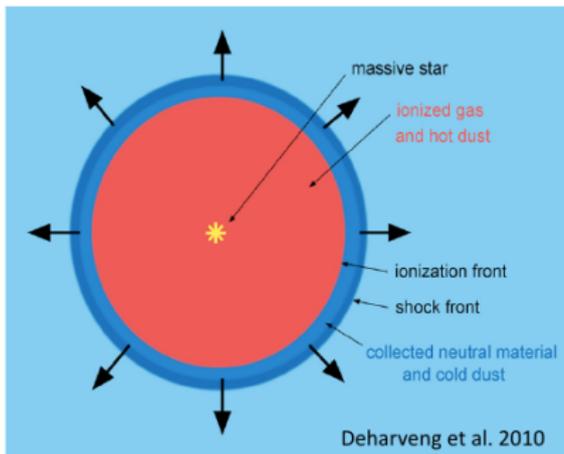
2 **Radiative driven implosion (RDI):**

- grumo denso pre-existente colapsa
- bordes de nubes brillantes

3 **Colisión de nubes moleculares:**

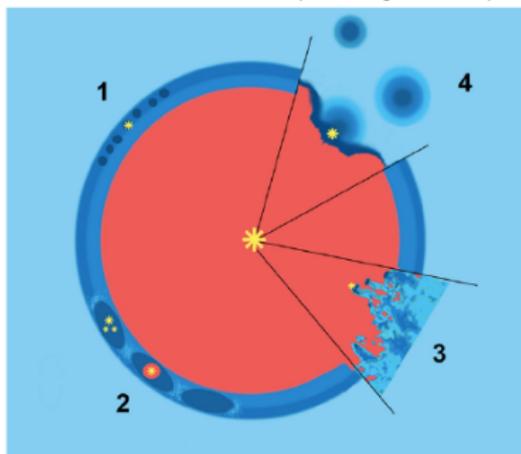
- Capa densa en la interfase
- Se cree que es el mecanismo frecuente en las colisiones de galaxias con discos

HII regions and star formation



Instabilities in the compressed shell:
Small-scale:
Low/intermediate mass
Star formation

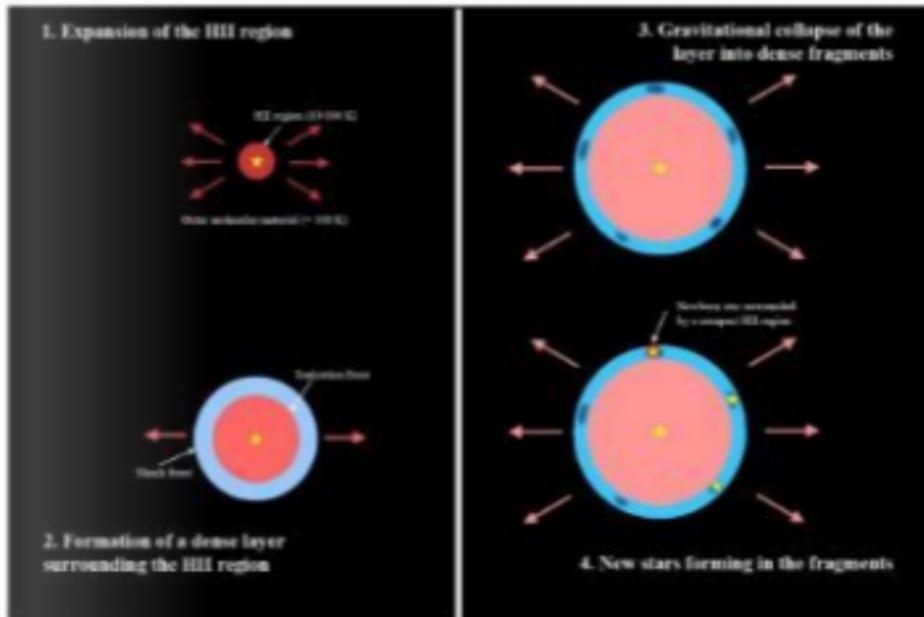
Radiation-driven compression
of pre-existing dense clumps



Instabilities in the compressed shell:
Large-scale: Massive Star formation
2nd generation HII regions
Clusters formation

Ionizing radiation acting
on a turbulent medium:
Pillar formation

Trigger the formation of (massive) stars by means of ionized regions expansion



Collect and collapse: formulaci3n anal3tica

$$t_{\text{frag}} \approx 1.56 \left(\frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{7/11} \left(\frac{Q_{\text{Ly}}}{10^{49} \text{ s}^{-1}} \right)^{-1/11} \\ \times \left(\frac{n_i}{10^3 \text{ cm}^{-3}} \right)^{-5/11} \text{ Myr},$$

$$R_{\text{frag}} \approx 5.8 \left(\frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{4/11} \left(\frac{Q_{\text{Ly}}}{10^{49} \text{ s}^{-1}} \right)^{1/11} \\ \times \left(\frac{n_i}{10^3 \text{ cm}^{-3}} \right)^{-6/11} \text{ pc},$$

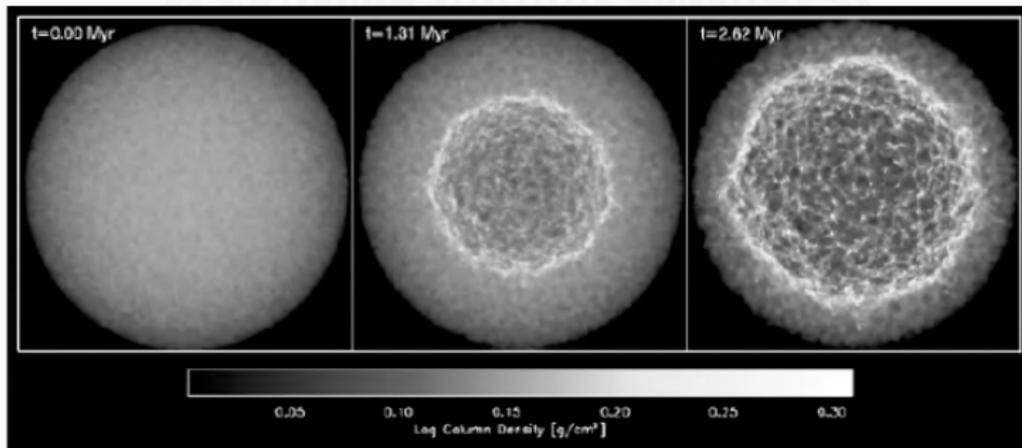
$$N_{\text{frag}} \approx 6.0 \times 10^{21} \left(\frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{4/11} \left(\frac{Q_{\text{Ly}}}{10^{49} \text{ s}^{-1}} \right)^{1/11} \\ \times \left(\frac{n_i}{10^3 \text{ cm}^{-3}} \right)^{5/11} \text{ cm}^{-2},$$

$$M_{\text{frag}} \approx 23 \left(\frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{40/11} \left(\frac{Q_{\text{Ly}}}{10^{49} \text{ s}^{-1}} \right)^{-1/11} \\ \times \left(\frac{n_i}{10^3 \text{ cm}^{-3}} \right)^{-5/11} M_{\odot}, \text{ and}$$

$$d_{\text{frag}} \approx 0.83 \left(\frac{a_s}{0.2 \text{ km s}^{-1}} \right)^{18/11} \left(\frac{Q_{\text{Ly}}}{10^{49} \text{ s}^{-1}} \right)^{-1/11} \\ \times \left(\frac{n_i}{10^3 \text{ cm}^{-3}} \right)^{-5/11} \text{ pc},$$

Whitworth et al. 1994, MNRAS 268, 291

Collect & Collapse

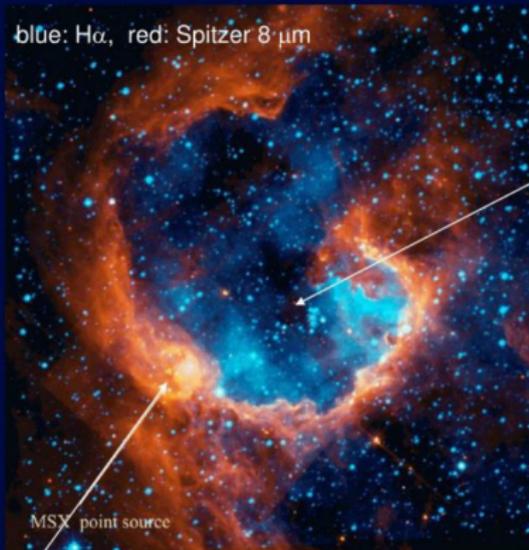


Dale, Bonnell & Whitworth 2007, *Mon. Not. Royal Astron. Soc.* **375**, p. 1291

We conduct smoothed particle hydrodynamics simulations of the 'collect-and-collapse' scenario for star formation triggered by an expanding H II region. We simulate the evolution of a spherical uniform molecular cloud with an ionizing source at its centre. We find that the shell driven by the H II region fragments to form numerous self-gravitating objects. We repeat our calculations at four numerical resolutions to ensure that they are converged. We compare our results to the analytical model of Whitworth et al. and show that our simulations and the predictions of Whitworth et al. are in good agreement in the sense that the shell fragments at the time and radius predicted by Whitworth et al. to within 20 and 25 per cent, respectively.

Triggered massive star formation in RCW 79

blue: H α , red: Spitzer 8- μ m



Zavagno et al. (2006, A&A 446,171):

central OB cluster,
including an O4 star ($\sim 60 M_{\odot}$)

Radius of HII region = 6.4 pc
for $n \sim 2000 \text{ cm}^{-3} \rightarrow \tau_{\text{dyn}} = 1.7 \text{ Myr}$
collected layer fragmented $\sim 10^5 \text{ yr}$ ago,
consistent with ages of YSOs

Data consistent with
"collect & collapse model"
fragmentation of the shocked dense
layer around an expanding HII region
Whitworth et al (1994)

compact HII region,
ionized by an O9 star ($\sim 20 M_{\odot}$),
contains many class I protostars

A&A 523, A6 (2010)

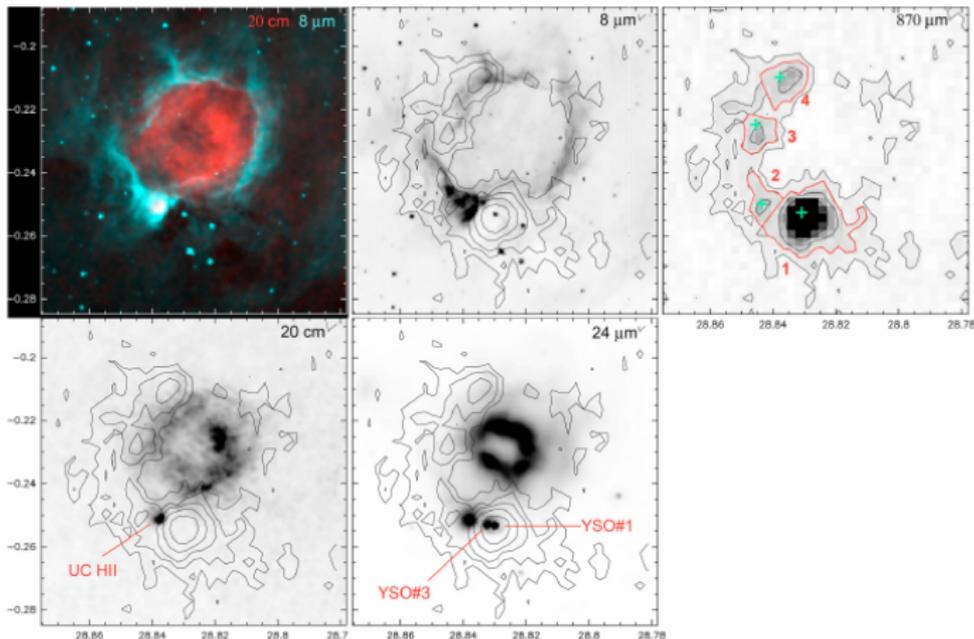
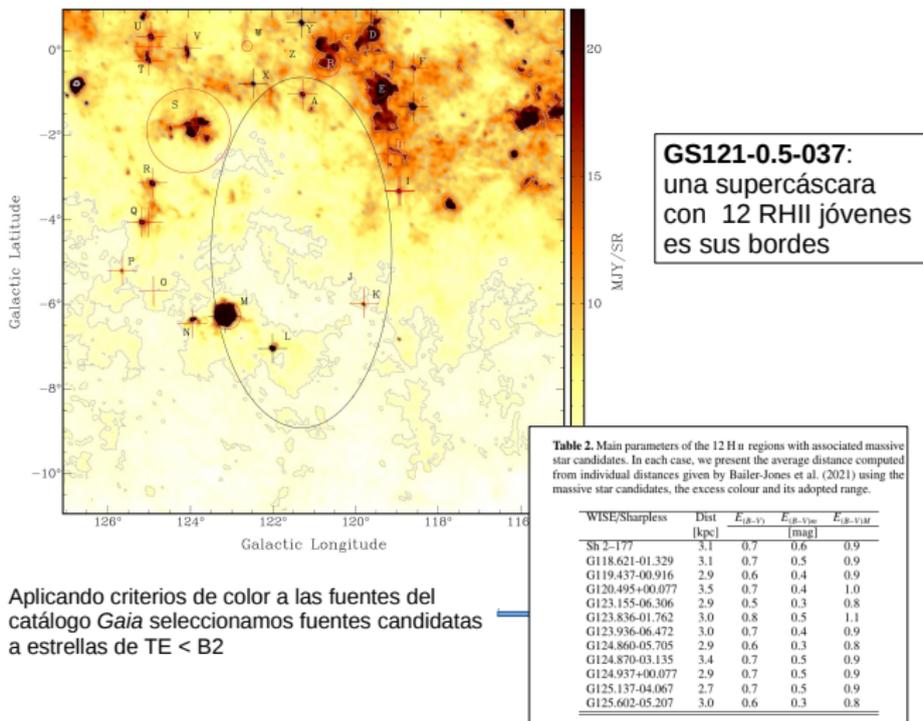


Fig. 18. N49. *Top left:* Spitzer-GLIMPSE 8.0 μm emission in turquoise and 24 μm emission in red. *Others:* contours of 870 μm emission superimposed to greyscale images at 8.0 μm , 870 μm , 20-cm, and 24 μm ; the 870 μm contour levels are 0.08 Jy/beam (used to define the limits of the collected shell), 0.25, 0.5, 1.0, and 2.0 Jy/beam. The red contours at 0.25 Jy/beam have been used to measure the integrated 870 μm flux of condensations 1 to 4. The green crosses indicate the NH_3 positions measured by Wyrowski & Wienen (in preparation; Table A.2). The massive stage I YSOs found by Watson et al. (2008) are indicated.

$\zeta\gamma$ alrededor de las supercáscaras?

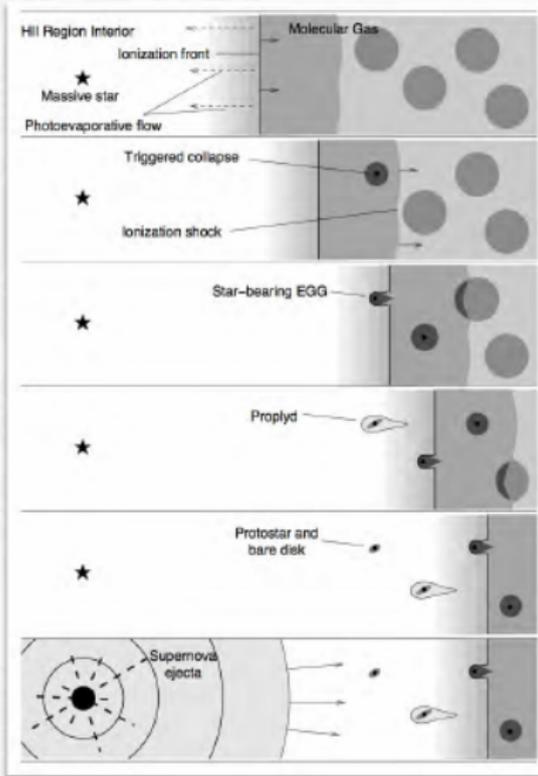
Emisión a $60\ \mu\text{m}$

Suad+(2022)



Evaporating Gaseous Globules

- 1) Radiation from a massive star drives an ionization front into surrounding molecular gas.
 - 2) The ionization front (plus winds and previous SNe) drive a shock, triggering collapse of molecular cores.
 - 3) ~100,000 years after triggered collapse, the ionization front overruns the core, forming an EGG.
 - 4) EGGs evaporate in ~10,000 years, exposing the disk. The evaporating disk is a proplyd.
 - 5) In ~10,000 years, disks erode to ~50 AU. Disk evaporation ends, leaving a protostar and bare protoplanetary disk.
 - 6) The massive star goes supernova, injecting newly synthesized elements into surrounding disks.
- From Hester & Desch (2005)



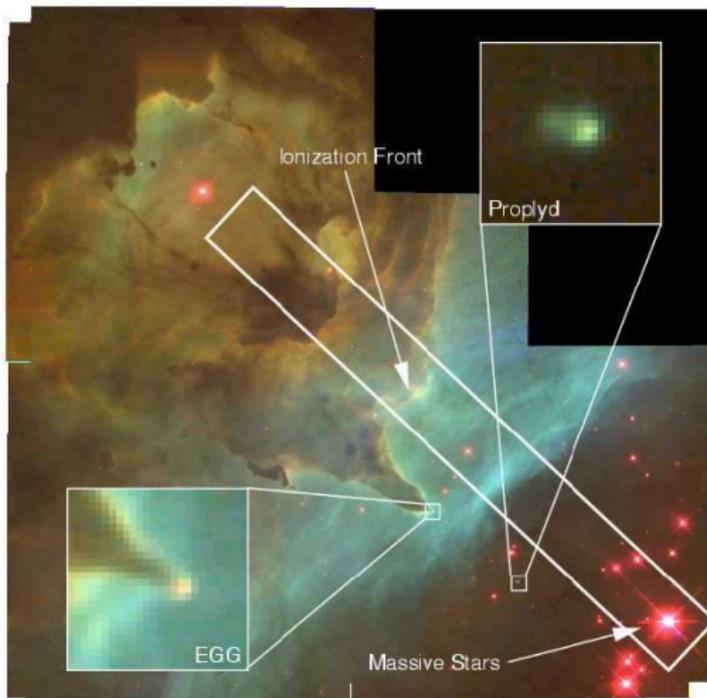
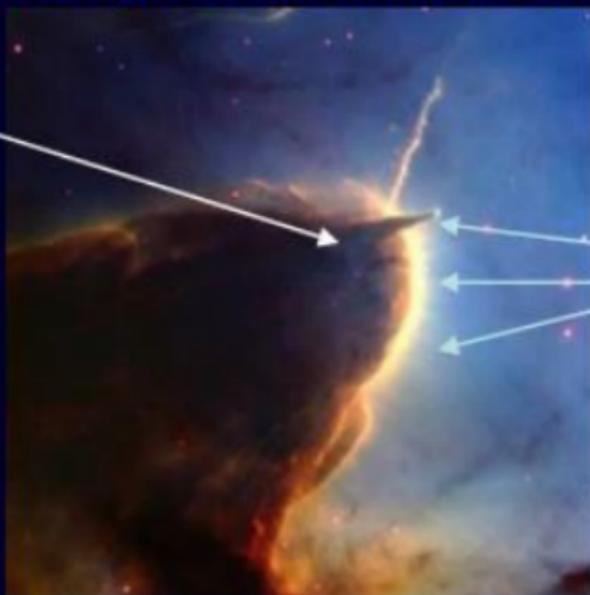


Figure 3. An *HST* WFPC2 image of the G353.2+0.9 HII region in NGC 6357 (Healy et al. 2004). This figure illustrates the astrophysical context for the sequence of events described in Figure 4.

The young stellar objects seen in the interiors of HII regions, such as the young stars, protostars, and “proplyds” did not form in the environments in which they reside today.

YSOs



O star



Trifid Nebula
HST, Hester
et al. (1999)

Star formation in irradiated globules:
"radiatively driven implosion"

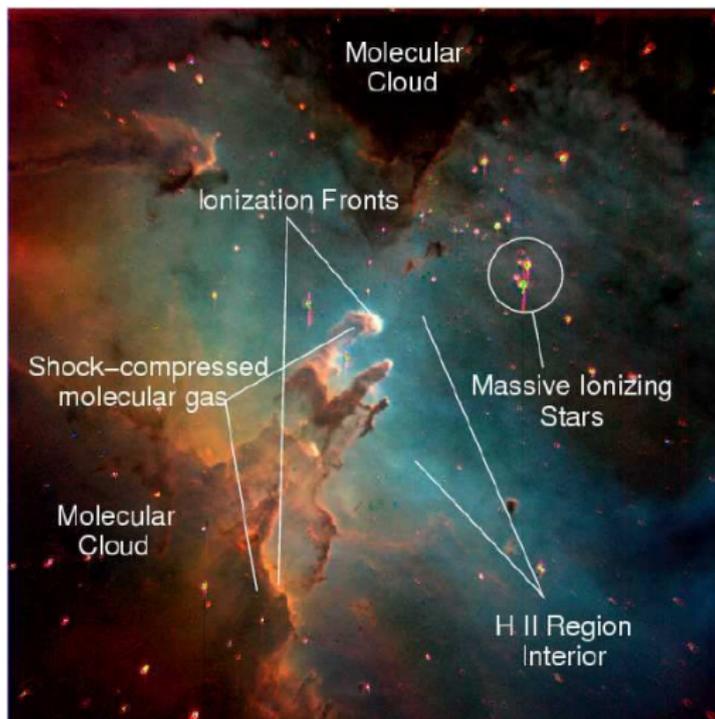
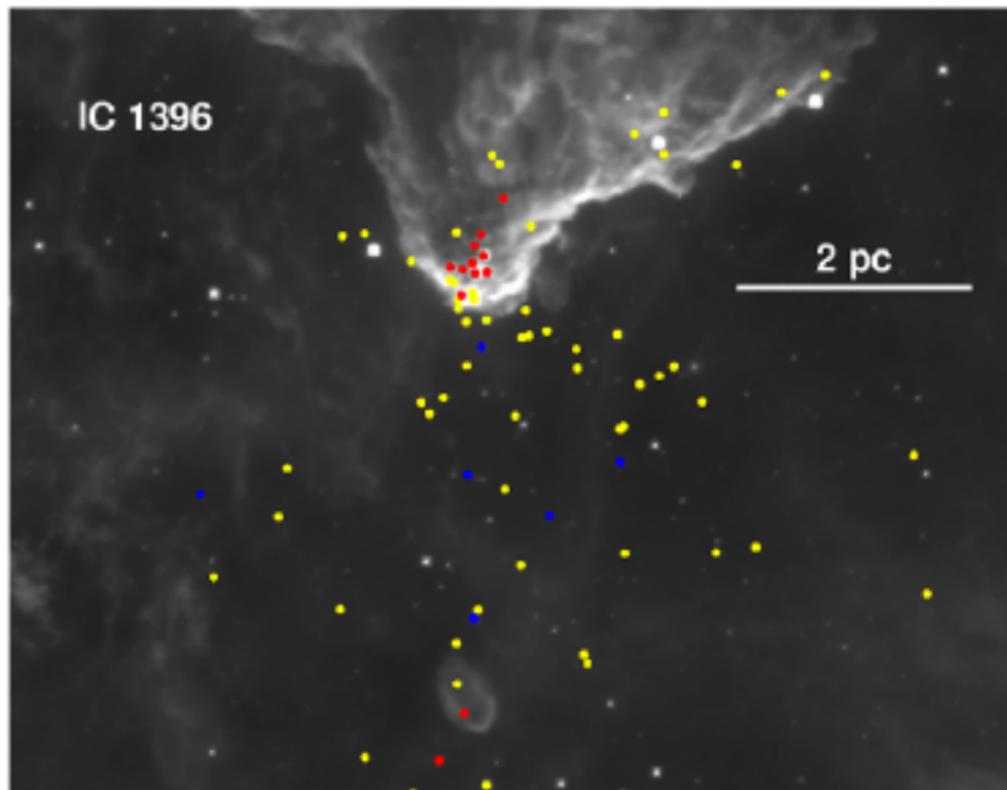


Figure 2. The structure of a blister H II region. This is a ground-based image of the Eagle Nebula, M16, obtained with the 1.5-m telescope at Palomar Observatory.

Shocks driven in advance of ionization fronts compress dense molecular gas surrounding H II regions.



Rojos: Clase 1, Amarillos: Clase 2

Formación estelar inducida: WR130

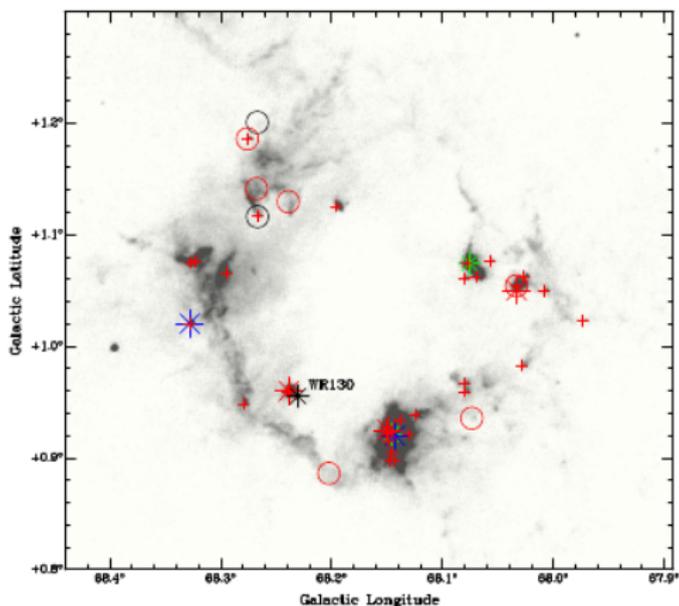


Figure 9. *Herschel* image at 70 μm with the location of the cYSOs superimposed. Green, blue, and red asterisks correspond to *IRAS* YSO, MYSO, and CH II candidates, respectively, while black and red circles indicate the location of *WISE* Class I and Class II candidate sources, respectively. *Herschel* sources are indicated by red crosses.

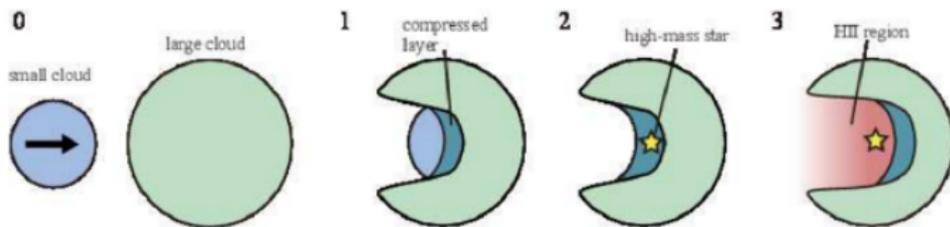
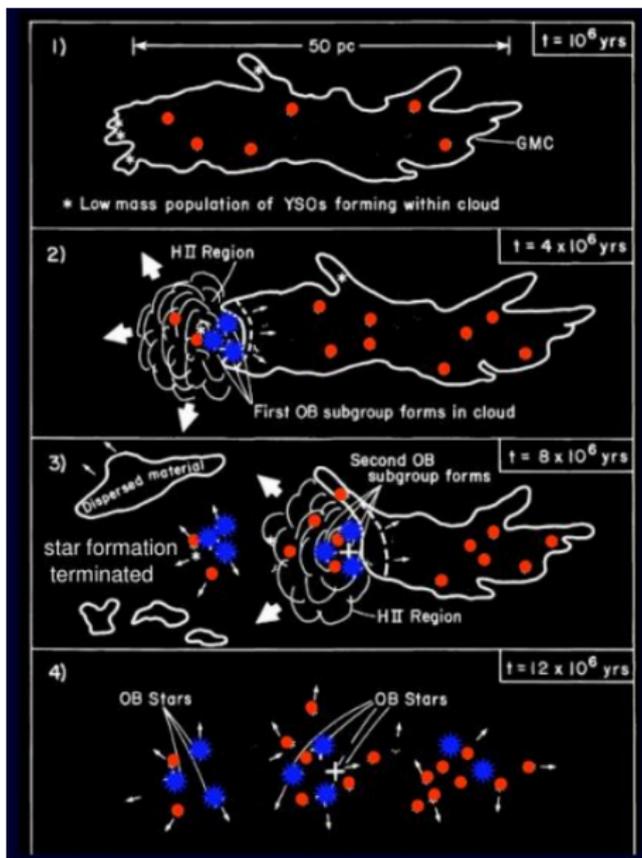
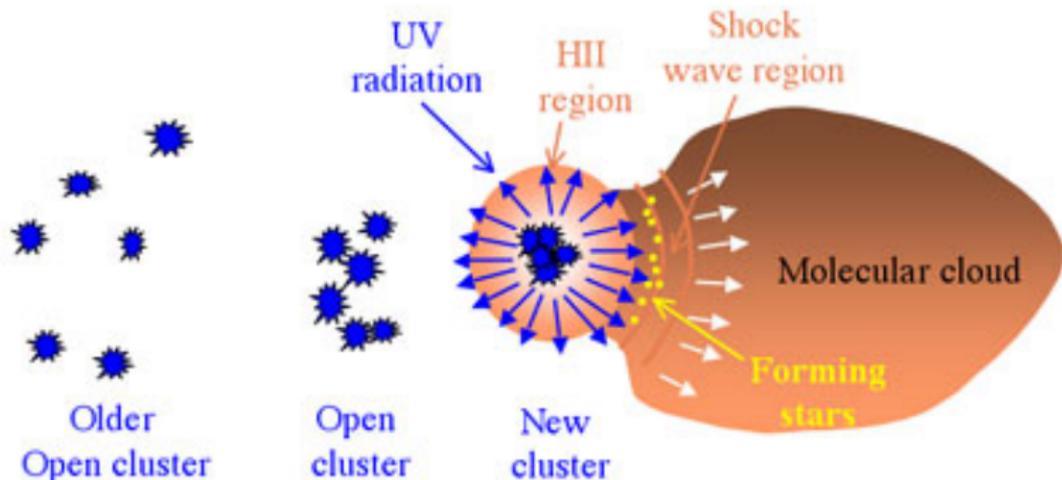


Figura 1.12: Esquema que muestra la formación estelar inducida por colisión de nubes moleculares. La fase 0 corresponde al estadio previo a la colisión. Las fases 1 a 3 muestran la secuencia temporal desde la colisión hasta la formación de una estrella. Tomada de [Fukui et al. \(2017\)](#).

Sequentially Triggered Star Formation in OB Associations



Sequentially Triggered Star Formation in OB Associations



Walch+(2015): Del abstract: ...By performing high-resolution, three-dimensional smoothed particle hydrodynamics simulations of HII regions expanding into fractal molecular clouds, we investigate whether the formation of massive clumps in dense, swept-up shells necessarily requires the CC mechanism.

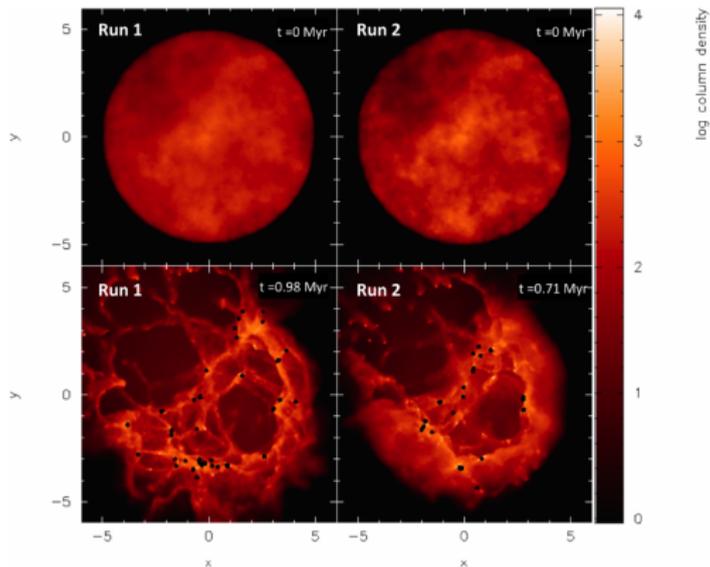
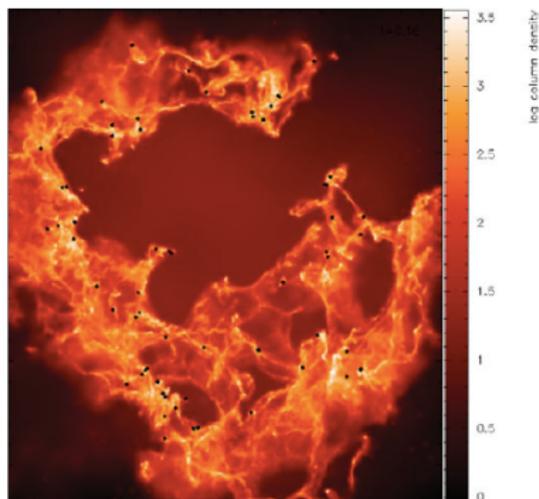
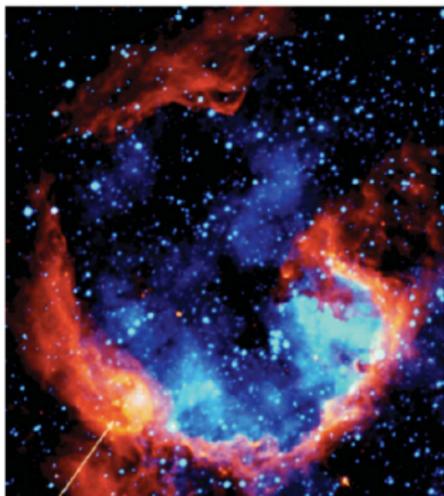


Figure 2. Upper panels: initial column-density distributions in $M_{\odot} \text{pc}^{-2}$ for the two runs. In both cases the initial conditions have been generated with the same fractal dimension, $D = 2.4$, and the same random seed, \mathcal{R} , but different scaling densities: $\rho_0 = 1.5$ (Run 1; left-hand column) and $\rho_0 = 1.0$ (Run 2; right-hand column). Lower panels: the column density distributions at t_{end} , after $\sim 500 M_{\odot}$ of the cloud (~ 5 per cent) has been converted into stars. The black dots mark sink particles, which represent forming protostars. Each frame is $12 \text{ pc} \times 12 \text{ pc}$.

In both Run 1 and Run 2, a star emitting hydrogen-ionizing photons at rate $N_{\text{LyC}} = 10^{49} \text{ s}^{-1}$ (O7.5) is placed at the centre of the cloud. The black dots in the evolved HII regions mark sink particles, which represent forming protostars.

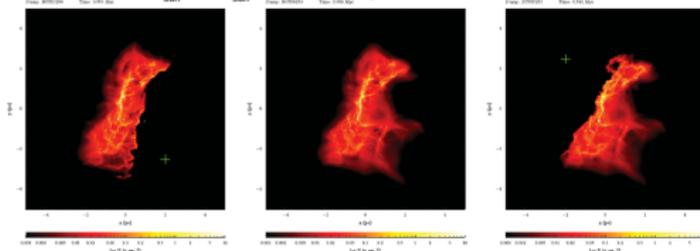
Walch+ 2012, 2013, 2015: expansion of an HII region in a fractal medium



a hybrid mechanism is at work, which combines elements of C&C and RDI; it is not standard C&C because at no stage does a coherent shell form and then become gravitationally unstable and fragment, but it relates to CC because the clumps do collect additional material, due to the expansion of the H II region

Muy difícil identificar qué estrellas se formaron de modo espontáneo y cuáles de modo inducido, o cuál es el impacto neto (acelerar el proceso (weak triggering), Dale+2007).

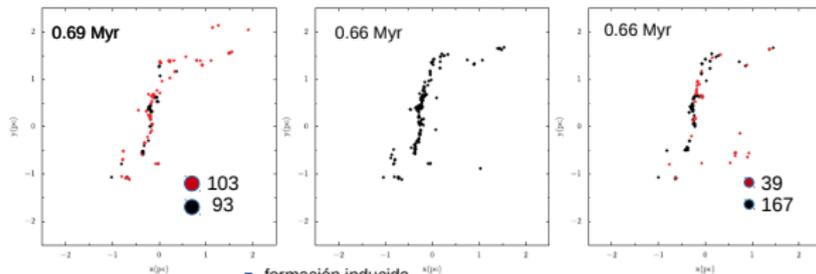
-0.67 Myr, $2.3 \times 10^3 M_{\text{sun}}$, 60 M_{sun} O star, nube elipsoidal, densidad uniforme, turbulencia



Fuente ionizante abajo

Sin fuente ionizante (control run)

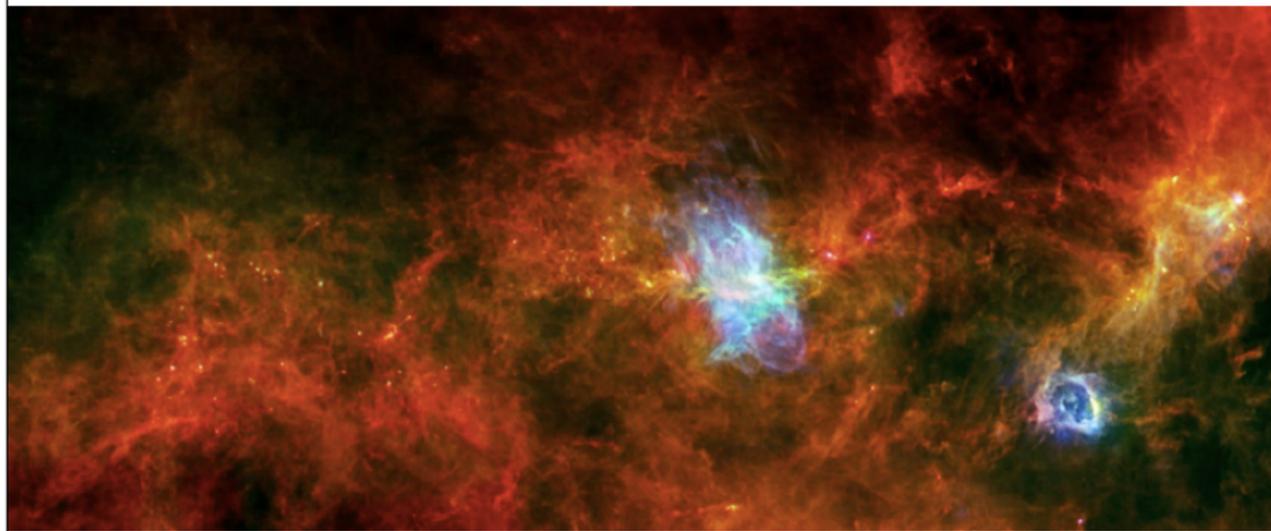
Fuente ionizante arriba



● formación inducida
● formación espontánea

Dale+2012

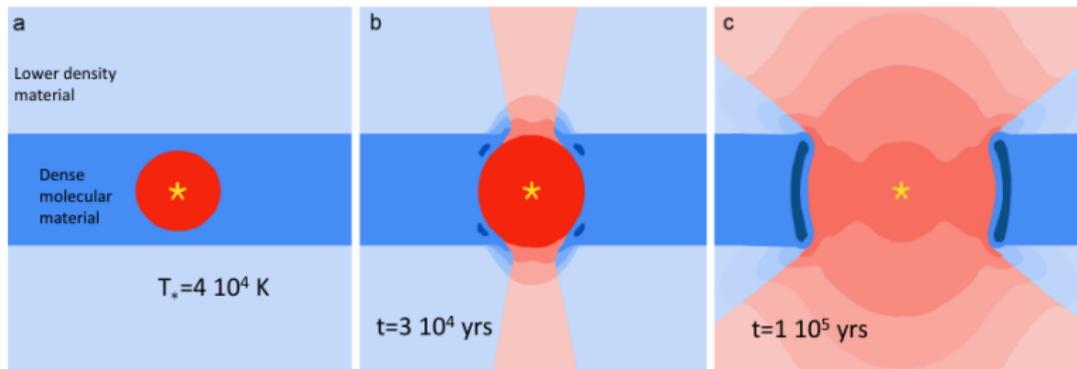
Vela C cloud and the RCW 36 bipolar region
70 160 250 μm (Minier et al. 2013)



Bipolar HII regions

High density compressed molecular material at the waist
Formation of a **taurus**

(Deharveng+ 2015)



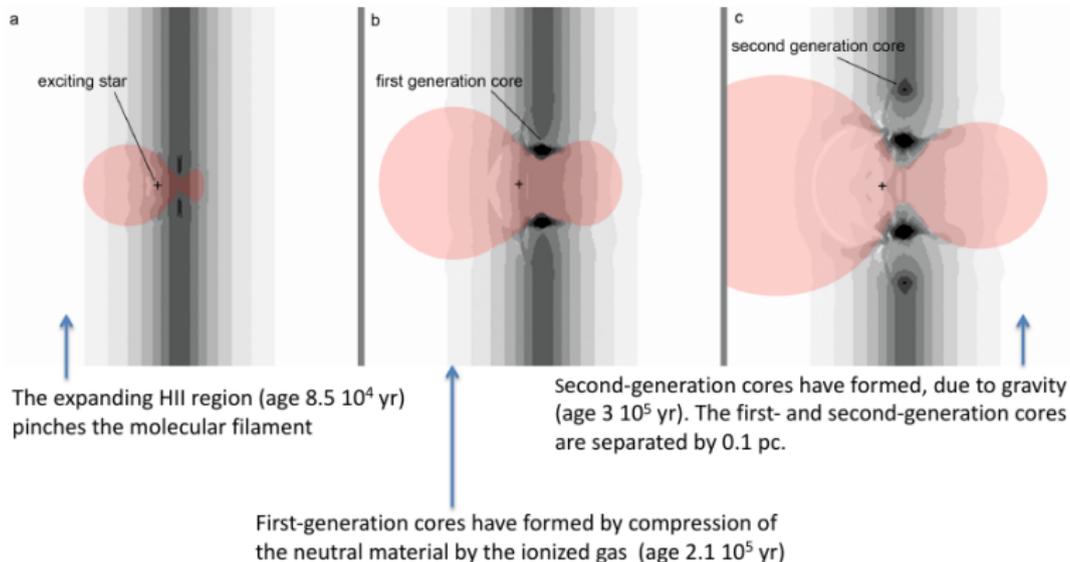
Formation of a bipolar HII region (simulation of Bodenheimer et al. 1979).

Thickness of the parental plane is 1.3 pc - density $300 \text{ H}_2 \text{ cm}^{-3}$

ionized material neutral material

Bipolar HII regions

Star formation triggered by the expansion of an HII region close to a filament (simulation of Fukuda & Hanawa 2000) neutral sound speed 0.3 km s^{-1} , Maximum density on the axis of the filament $2 \times 10^6 \text{ cm}^{-3}$ exciting star at 0.025 pc of the filament's axis.



Supernova
Explosion



Cold Clouds of
Gas & Dust

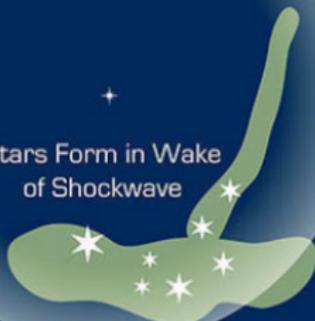
(a)



Shockwave Compresses
Clouds

(b)

Stars Form in Wake
of Shockwave



(c)

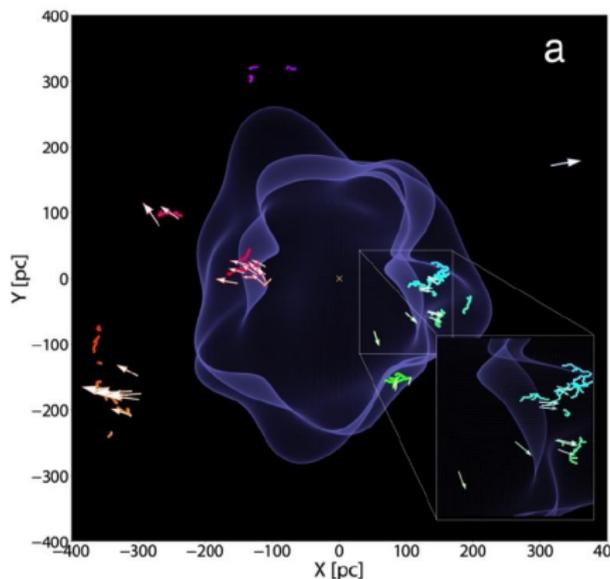


Spitzer Image
(Henize 206)

Spitzer Space Telescope • ssc2004-04b

Star formation near the Sun is driven by expansion of the Local Bubble

Zucker+2022, Nature 601



Ophiuchus, Pipe, Lupus, and Corona Australis