From Interstellar Clouds to Star-Forming Galaxies:
Universal Processes?
Proceedings IAU Symposium No. 315, 2015
P. Jablonka, Ph. André & F. van der Tak, eds.

doi:10.1017/S1743921316007419

A multi-wavelength classification system for the evolution of star clusters

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Abstract. The availability of high spatial resolution molecular gas observations from ALMA, and similar resolution observations in the radio continuum using the VLA, is providing the opportunity to make comparisons with specific features seen in optical observations more directly than in the past. Using our ALMA observations of the Antennae galaxies as a springboard, we have compared the locations of small-scale CO (3–2) features with a variety of multi-wavelength observations, in particular optical and near-infrared imaging using both broad (UBVI) and narrow-band data (H_α and Pa_β) taken with the HST, and radio (3.6 cm) continuum observations taken with the VLA. This comparison leads to the development of an evolutionary classification system which provides a framework for studying the sequence of star cluster formation and evolution, from diffuse Giant Molecular Clouds (GMCs), to proto, embedded, emerging, young, and intermediate/old star clusters. Using this evolutionary framework, we estimate the maximum age range of clusters formed in a single GMC is approximately 10 Myr. This suggests that the molecular gas is removed over this timescale, resulting in the cessation of star formation and the destruction of the GMC within a radius of about 200 pc.

1. Introduction

In the past, the difference in spatial resolution for optical observations (e.g., 0.1″ with the *Hubble Space Telescope* = HST) and radio observations (typically a few ″s) has been a limiting factor for many studies. With the advent of ALMA (the *Atacama Large Millimeter/submillimeter Array*), and the *Very Large Array* (VLA), we have entered a new era where it is possible to study all three components with comparable resolution.

Figure 1 shows an illustrative example from the Antennae galaxies, as described in more detail in Whitmore *et al.* (2014). The background images are HST observations; the green contours show CO (3-2) observations from ALMA; the yellow contours are radio continuum (3.6 cm) observations from the VLA, and the orange shows age and extinction estimates for several star clusters based on HST observations from Whitmore *et al.* (2010). Evolutionary stages, as discussed below, are included in blue.

As shown in Figure 1, regions with diffuse CO emission (i.e., GMCs) have neither optical clusters or radio continuum emission associated with them. The youngest star clusters, with ages around 1 Myr and Av extinctions greater than about 1 mag, have both CO and radio continuum emission. For the older clusters, with ages greater than about 5 Myr, there is no CO or radio continuum emission. Hence, region W10-3 provides a clear story line of how clusters form and evolve in the Antennae galaxies.

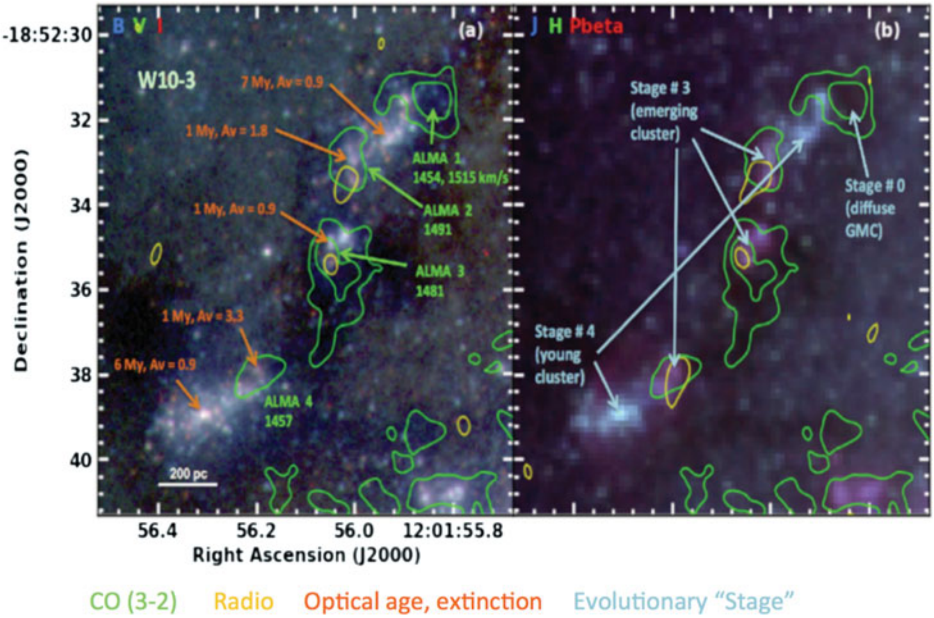


Figure 1. Correspondence between CO knots (green), 3.6 cm radio emission (yellow) and optical star clusters (orange) in W10-3 (from Whitmore *et al.* 2014). *(A color version of this figure is available online.)*

2. A Multi-Wavelength Classification System

Other regions in the Antennae show similar correlations as those found in W10-3. Based on these results, and expanding on earlier schemes discussed in Johnson (2002, 2005) and Whitmore *et al.* (2011), we developed a classification system for the evolution of star clusters from GMCs to old globular clusters, as outlined in Figure 2.

Below we provide a brief description; see Whitmore *et al.* (2014) for more details.

Stage 0 (**diffuse giant molecular clouds**) [turbulent equilibrium] - Knots of diffuse CO emission are detected, but no radio, or optical/near-IR emission is observed.

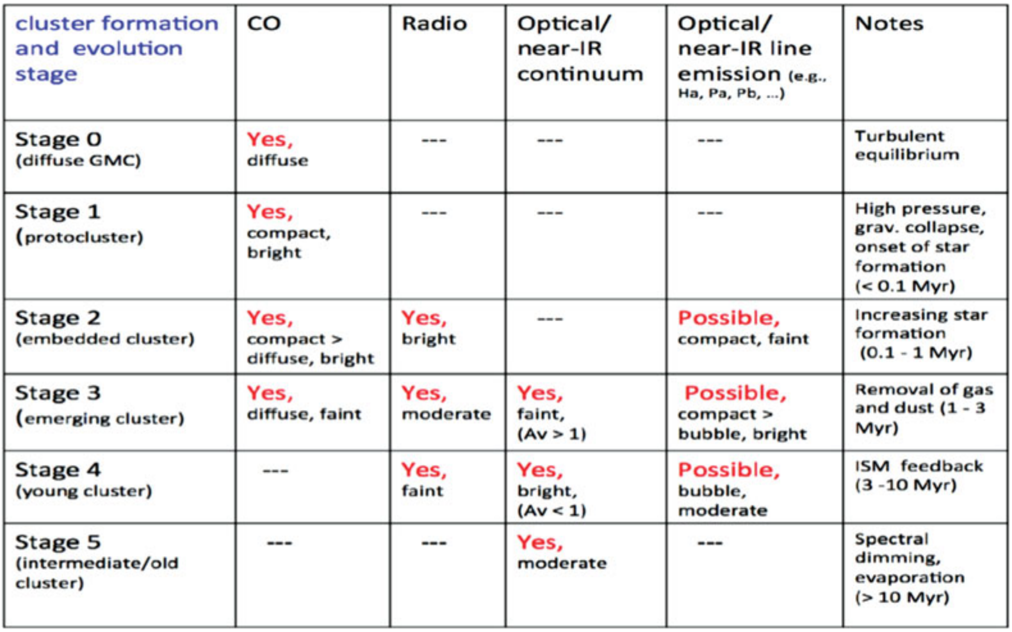
Stage 1 (**protocluster**, <0.1 Myr) [high pressure, gravitational collapse] - Compact CO emission is detected, but no radio or optical/near-IR emission is observed.

Stage 2 (**embedded cluster**, 0.1 - 1 Myr) [onset of star formation] - Thermal radio emission is detected along with CO emission. No optical/near-IR continuum is observed, but weak line emission may be present if an O star has formed. The very recently formed cluster is deeply embedded in its natal gas during this stage.

Stage 3 (**emerging cluster**, 1 - 3 Myr) [removal of gas and dust] - The very young cluster is observed primarily in the radio, optical/near-IR emission lines, and faintly in the optical continuum. The cluster is moderately extincted by dust, with A_V typically >1 mag.

Stage 4 (**young cluster**, 3 Myr - 10 Myr) [ISM feedback] - The cluster is increasingly observable in the optical and in optical/near-IR emission lines (the latter typically in the form of bubbles) due to the removal of much of the natal gas and dust by feedback. CO emission is gone, but weak radio continuum emission is still observed in many cases. The A_V values have dropped to <1 mag.

Stage 5 (**intermediate/old clusters**, >10 Myr) [spectral dimming, evaporation] - The cluster is observed in the optical/near-IR, although it has faded, and ionized gas is no longer observed since the massive stars have evolved into stellar remnants.



cluster formation and evolution stage	CO	Radio	Optical/ near-IR continuum	Optical/ near-IR line emission (e.g., Ha, Pa, Pb, …)	Notes
Stage 0 (diffuse GMC)	Yes, diffuse	---	---	---	Turbulent equilibrium
Stage 1 (protocluster)	Yes, compact, bright	---	---	---	High pressure, grav. collapse, onset of star formation (< 0.1 Myr)
Stage 2 (embedded cluster)	Yes, compact > diffuse, bright	Yes, bright	---	Possible, compact, faint	Increasing star formation (0.1 - 1 Myr)
Stage 3 (emerging cluster)	Yes, diffuse, faint	Yes, moderate	Yes, faint, (Av > 1)	Possible, compact > bubble, bright	Removal of gas and dust (1 - 3 Myr)
Stage 4 (young cluster)	---	Yes, faint	Yes, bright, (Av < 1)	Possible, bubble, moderate	ISM feedback (3 -10 Myr)
Stage 5 (intermediate/old cluster)	---	---	Yes, moderate	---	Spectral dimming, evaporation (> 10 Myr)

Figure 2. Matrix showing the definition of the various stages of cluster formation and evolution used in the classification framework (from Whitmore *et al.* 2014).

3. Other Regions in the Antennae - the "Long-Thin Filament" and the "Firecracker"

Figure 3 shows a more populated region in the Antennae that contains all six evolutionary stages from the matrix in Figure 2. The region has been nicknamed the Long-Thin Filament due to the presence of a 3 kpc CO filamentary structure with an internal velocity dispersion less than 10 km/s (Whitmore *et al.* 2014).

Another region discussed in Whitmore *et al.* (2014) is Super Giant Molecular Cloud 2 (SGMC2), first defined in Wilson *et al.* (2000). A particularly interesting feature is a compact (radius less than 24 pc), high mass (greater than 5×10^6 $M_\odot$), region with intense compact CO emission but no radio emission. This would be a Stage 1 (protocluster), as defined in Figure 2. See Johnson *et al.* (2015) for a detailed discussion of this system, which has been nicknamed the Firecracker.

4. The Timescale for GMC Destruction

An example of the utility of the classification system is provided by estimating the destruction time of GMCs once star formation has started. This is determined by counting the relative fractions of objects in each evolutionary stage. The resulting estimate for the maximum age range of clusters in a GMC after star formation has started is less than 10 Myr, after which time the GMC has been destroyed within a radius of about 200 pc, probably by feedback from the cluster (Whitmore *et al.* 2014). Note that this timescale is consistent with region W10-3 shown in Figure 1, since no CO emission is associated with the older (6 and 7 Myr) clusters. Similar calculations have been made by Kawamura *et al.* (2009) and by Miura *et al.* (2012), resulting in estimates of somewhat longer GMC destruction time scales (i.e., 20 40 Myr).

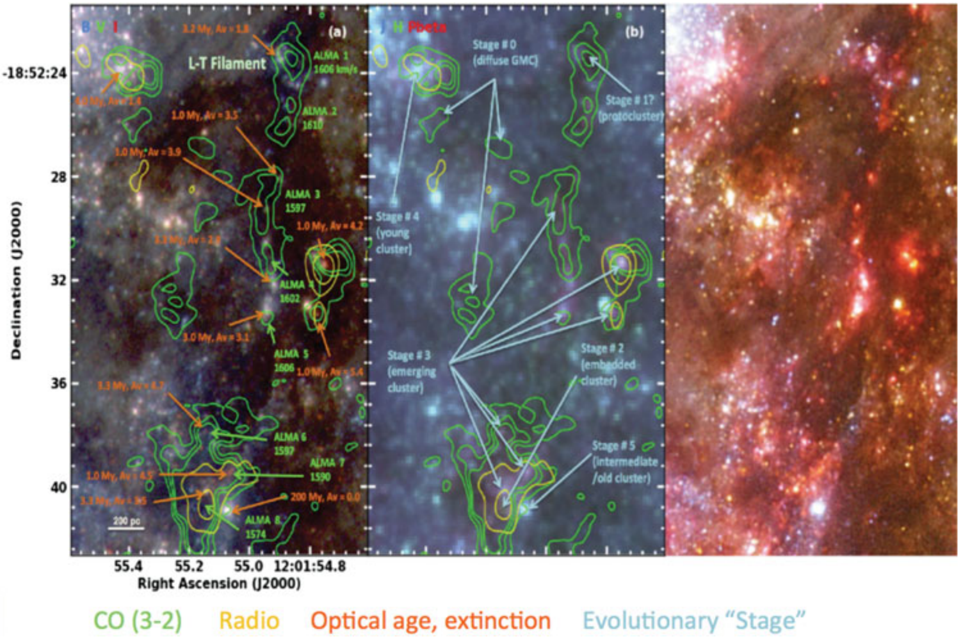


Figure 3. Correspondence between CO (3–2) knots, 3.6 cm radio emission and optical star clusters in the Long-Thin (L-T) Filament. The same color scheme as defined in Figure 1 is used (from Whitmore *et al.* (2014)). *(A color version of this figure is available online.)*

5. Summary

1. The availability of similar resolution CO (ALMA), radio continuum (VLA), and optical/near-IR (HST) makes it easier to compare features and find patterns.

2. This leads to the development of a multi-wavelength evolutionary classification system ranging from diffuse GMCs (stage 0) to old globular clusters (stage 5).

3. Two particularly interesting objects in the Antennae are the Long-Thin Filament (a 3 kpc long CO emission filament with a velocity dispersion less than 10 km/s) and the Firecracker (a candidate protocluster with a radius less than 24 pc and mass greater than 5×10^6 $M_\odot$).

4. Using this classification system leads to an estimate of less than 10 Myr for the destruction time of a giant molecular cloud due to feedback from the young star clusters.

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