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The lifecycle of molecular clouds and the extragalactic side of Francesco

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Abstract. I outline the interest of Francesco for star formation in nearby galaxies and the main results of the latest project Francesco was interested in and actively working at. This involves the association between giant molecular clouds (GMCs) and young stellar cluster candidates (YSCCs) in M33. The GMCs have a remarkable spatial correlation with infrared selected YSCCs, stronger than with Hα or optically selected sources, with a typical separation of 17 pc. Through age estimates of the YSCCs, and a classification of GMCs according to various evolutionary stages, we estabish that 14 Myrs is a typical lifetime of a GMC in M33 with the inactive and embedded phases lasting about 4 and 2 Myrs respectively.

Key words. Galaxies: individual: M33 – Galaxies: star formation – Galaxies: ISM – ISM: molecules – infrared: ISM

1. Introduction

Francesco has always had an interest in extragalactic studies not only because of his general curiosity but also because he believed that they can complement the investigation of our Galaxy to draw a comprehensive picture of the process of star formation in space and time. We shared the organization of three international conferences in Spineto involving the trasformation of gas into stars from small scales to intergalactic filaments: IMF@50(2004), SFR@50(2009), IGM@50(2015). It has been a great unforgettable experience fighting together to find the best venue, the best speakers, the best social events for the meetings. And what I have learned from him is that kindness and time dedication to each participant is a very important ingredient for a successful conference.

While he was director of the Arcetri Astrophysical Observatory he supported postdoc fellowships to study the ISM and star formation in nearby galaxies. Futhermore he is also co-author of a few papers on extragalactic topics. Francesco was actively participating to projects concerning the first phases of star formation in nearby galaxies and in particular, in 2015 we were collaborating for the determination of the duration of the various phases of the molecular cloud lifetime in the nearby galaxy M33. Unfortunately the project has not been completed before he passed away and some of his suggestions and ideas are left in the drawer. I will describe in the next Sections some results published in what is today his latest publication (Corbelli et al. 2017). Francesco liked highly peaked clouds in the M33 survey, and one of these is shown in Figure 1. The complex has a total gas mass of 1.4 10^6 $M_\odot$, is located at

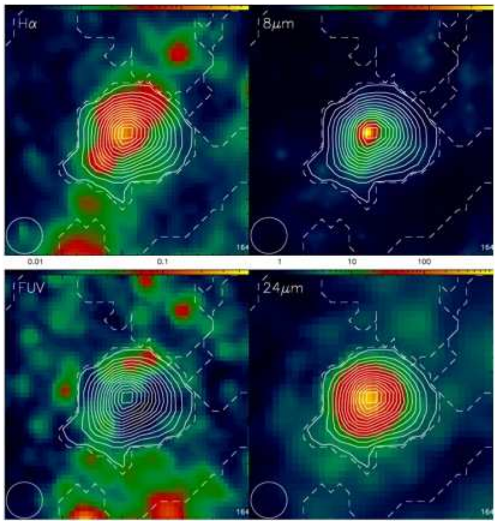

Fig. 1. The CO J=2-1 integrated intensity contours for Francesco's favorite M33 giant molecular cloud (GMC178) are plotted on maps of Hα (*upper left panel*), GALEX-FUV (*lower left panel*), Spitzer 8 μm (*upper right panel*) and Spitzer 24 μm (*lower right panel*)

800 pc from M33 center and hosts a YSCC of about 10^5 M⊙, detected in the mid-IR and Hα but not in far-UV because of extinction.

2. GMCs and YSCCs in M33

Stars form from gas and leave their imprint on the gas through cloud dispersal or gas compression for the next generation of stars. Validating a cloud formation and evolution model requires an unbiased survey of molecular clouds and of star-forming sites in a galaxy. The CO (J=2-1) IRAM all-disk survey (Druard et al. 2014) has been used to identify and classify 566 GMCs with masses between $2{\times}10^4$ and $2{\times}10^6$ $M_\odot$ across the whole star-forming disk of M33. The number of GMCs above the survey completeness limit ($L_{CO} \geq 5700$ K km s^{-1} pc^2 or $M_{H_2} \geq 6.3 \times 10^4$ $M_\odot$) is 490. Following Gratier et al. (2012) molecular clouds are classified into three broad categories: clouds without obvious star formation (A), clouds with embedded star formation (B), and clouds with exposed star formation (C). Clouds with embedded or exposed SF are identified from the emission at 8 or 24 μm, which in C-type clouds is associated with Hα and often with far-UV (FUV) emission peaks, while B-type clouds have no optical counterpart. An example of C-type cloud is shown in Figure 1. The GMC classes correspond to different cloud evolutionary stages: inactive clouds are 32% of the total and classified clouds with embedded and exposed star formation are 16% and 52% of the total, respectively.

Table 1. YSCC classification

Cl.	main properties	YSCCs
b	GMC, embedded SF	97
c	exposed SF (c1+c2+c3)	(410)
c1	GMC, Hα, MIR coincident	55
c2	GMC, Hα, MIR, FUV coinc.	216
c3	no GMC, FUV, weak Hα	139
d	GMC, ambiguous	19
e	no GMC, no opt. counterp.	104

In the same area of the M33 disk, there are 630 YSCCs that we identified using Spitzer-24 μm data (Sharma et al. 2011; Corbelli et al. 2017). Some YSCCs are embedded star-forming sites, while the majority have GALEX-UV and Hα counterparts with estimated cluster masses and ages. We classify YSCCs into b-type (embedded within a GMC), c-type (exposed YSCC associated or not with a GMC) and e-type (mid-infrared source not associated with a catalogued GMC). A few ambiguous GMCs and YSCCs are in class D and d respectively. The full YSCC classification scheme and a summary of the resulting number of YSCCs in each class is shown in Table 1. The spatial correspondence between the position of GMCs and that of YSCCs has been studied by accurately inspecting the area that is covered by each GMC and by computing the positional correlation function of the two distributions. If $\bar{d}$ is the typical separation length between YSCCs, we expect to find only 20% of the GMCs with a YSCC at a distance shorter than $0.5\bar{d}$ if they are randomly distributed. Instead, we find fractions on the order of 60-70 %. The correlation length is on the order of 17 pc, but there is a highly statistically significant clustering out to larger distances.

Fig. 2. Francesco with Maarten Schmidt at Spineto during the SFR@50 meeting.

Inspired by work on the Large Magellanic Cloud (Fukui et al. 1999; Yamaguchi et al. 2001; Kawamura et al. 2009) and thanks to his knowledge of the star forming process and of Milky Way star forming regions, Francesco was hoping to find in M33 examples of the various evolutionary phases of star formation and to determine the relative timescales using the location of YSCC emission at various wavelengths and the physical caracteristics of GMCs. In the paper Corbelli et al. (2017) we have determined only the duration of the three main phases of star formation in M33 assuming that this is a continuous process.

3. Duration and properties of the molecular cloud lifecycle

The estimated ages of most YSCCs with optical counterparts and associated with C-type GMCs are between 3.5 and 8 Myr (Sharma et al. 2011; Corbelli et al. 2017) with a marked peak around 5 Myr. It is then reasonable to assume that the exposed star forming phase, from when some cluster radiation breaks through the cloud to the starting of the gas dissipation phase, lasts 8 Myr. Using the fractions of GMCs in each class we estimated the GMC lifetime in M33 to be 14.2 Myr, from the time when most of the cloud mass is assembled to the switch-off of the stellar cluster formation process, prior to gas dispersal (or to the trigger of a new star formation episode). This seems comparable to galactic GMC estimated lifetimes and somewhat shorter than GMC lifetimes in the LMC (Yamaguchi et al. 2001; Kawamura et al. 2009). The embedded phase, when mid-IR emission is visible but no Hα or FUV cluster radiatoin is detected, is the shortest phase and lasts 2.4 Myr. The duration of the cloud inactive phase from when the cloud is assembled to the starting of the star formation process is 3.8 Myr. The average CO luminosity increases from A- to B- to C-type clouds, and this suggests that GMC mass may continue to grow as they evolve from the inactive phase to the formation of massive stars. GMCs and YSCCs follow the HI filaments, except in the outermost regions, where the survey finds fewer GMCs than YSCCs, which is most likely due to undetected clouds with low CO luminosity. If this is the case, there is not much difference in the duration of the cloud lifecycle across the M33 disk (Corbelli et al. 2017). The processes that trigger the formation and the evolution of GMCs across the M33 disk are under investigation.

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