The History of Star Formation in the Large Magellanic Cloud

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1. Introduction

The history of star formation in the Magellanic Clouds greatly differs from that in our own Galaxy and, despite the many efforts it is still poorly known.

Studying the luminosity functions (LFs) of field stars of the Large Magellanic Cloud (LMC), Butcher (1977) first suggested that the bulk of stars formed about 3–4 Gyrs ago. Subsequently, Stryker (1984), Frogel & Blanco (1983), and Hardy et al. (1984) confirmed this conclusion.

However, all those results were based either on data at the limits of reliability of photographic photometry or made use of age calibrators that were affected by significant uncertainties.

Recently, Bertelli et al. (1992) proposed a new method based on suitable ratios of star counts in the Colour-Magnitude Diagram (CMD) and used it to analyse CMDs of three areas approximately located at 4° north from the LMC centre. These areas, named from the nearest cluster, are NGC 1866, NGC 1783, and NGC 2155. They concluded that star formation underwent an intense burst-like episode of activity (other kinds of star formation did not lead to satisfactory results) and that this prominent activity commenced at nearly the same epoch (3–4 Gyrs ago) in each region. Bertelli et al. (1992) thus confirmed the conclusions reached in the older studies, i.e. that the LMC has been quiescent for about 70 % of its history.

This kind of star formation is compatible with the age distribution of star clusters in LMC, whose vast majority is not older than 3–4 Gyrs (Chiosi et al. 1988, Da Costa 1991, Girardi et al. 1994).

However, despite the above hints about the history of star formation in LMC, there are still several questions to be addressed: Has this burst affected the whole LMC? What is the physical process responsible for the star formation enhancement 3–4 Gyrs ago? How was the star formation rate at ages older than 3–4 Gyrs?

To this aim, a programme has been undertaken to observe with the ESO telescopes at La Silla several selected areas all across the LMC (and SMC) and get deep, good quality B, V CCD photometric data. As part of this programme, frames for six regions have already been acquired. The six areas are located approximately at the centre of the V-charts of the Hodge & Wright (1967) catalogue after which they are named. The areas in question are LMC-30, LMC-45, LMC-56, LMC-61, LMC-60, and LMC-69. They are shown in Figure 1 superposed to a map of the LMC reproduced from Smith et al. (1987) indicating several regions of star formation, like 30 Doradus and Constellations II and III.

This paper presents the preliminary results for the region LMC-56 and a progress report of the overall programme.

2. The Data

The observations of the six fields have been taken during two observing runs in December 1991 and November 1993 using the 2.2-m ESO telescope equipped with EFOSC2 and the Thompson ESO CCD #19.

In the fields observed in the first run (LMC-56, LMC-69 and LMC-60) about 4,000 stars are measured down to V ~ 23 mag because of the mean seeing of 1.5″, whereas owing to the better seeing conditions (about 1.0″) in the fields observed in the second run (LMC-30, LMC-45 and LMC-61), about 9,000 stars per frame are detected down to V ~ 24 mag.

Figure 2 shows the BV-CMD of one area, namely LMC-45.

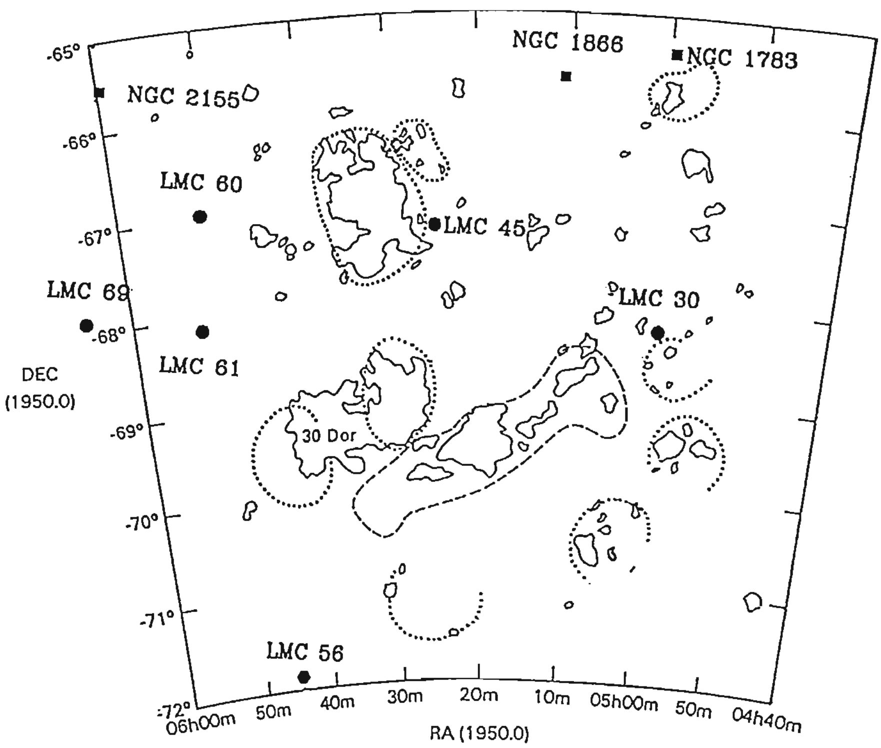

Figure 1: *The map of LMC reproduced from Smith et al. (1987). In this map are shown both regions of ongoing (30 Doradus) or very recent star formation (Constellation III), together with the selected areas. The filled squares indicate the three regions studied by Bertelli et al. (1992), the filled diamond shows LMC-56 presented in this paper, finally the filled circles mark the remaining areas of the programme.*

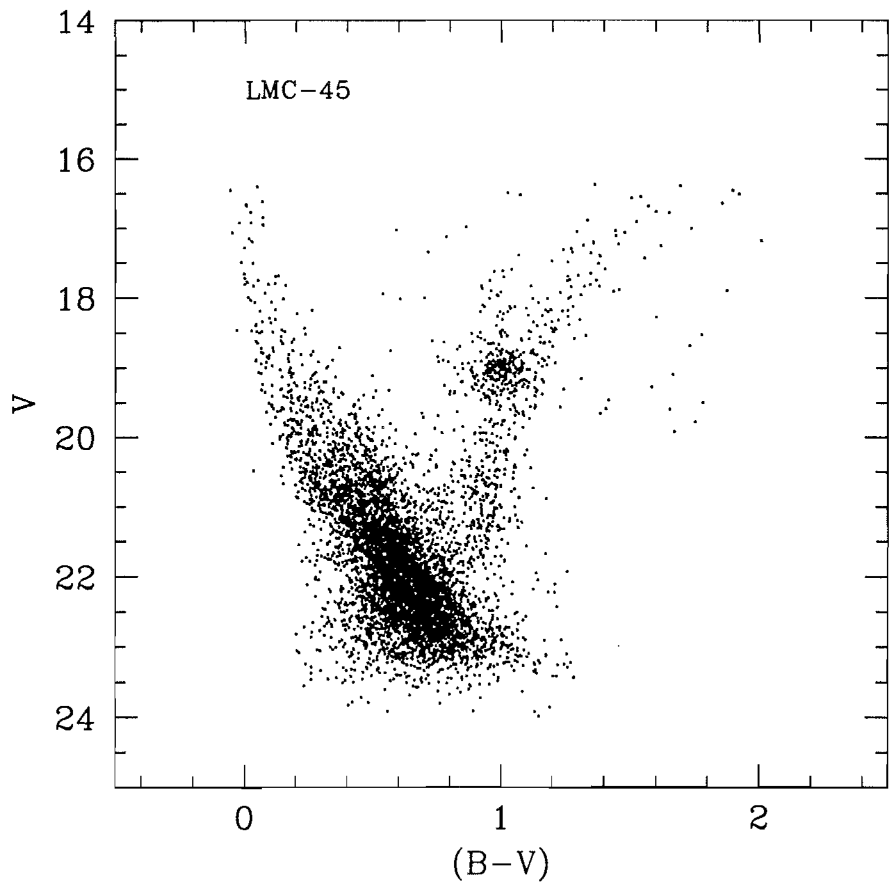

Figure 2: *CMD of the region LMC-45.*

3. Theoretical Rationale

The Bertelli et al. (1992) method is based on the use of suitable ratios of star counts effected in the giant and main sequence regions of the CMDs and their comparison with the CMDs and their comparison with theoretical simulations at varying laws of star formation. This is parameterized by the age of the initial episode and the intensity.

The analysis is made by means of the library of theoretical isochrones of Bertelli et al. (1994), which is based on the stellar models of Bressan et al. 1993) and Fagotto et al. (1994 a, b) calculated with core and envelope overshoot, the new radiative opacities of Iglesias et al. (1992), and a large range of metallicities (from Z=0.0004 to Z=0.05). In addition to this, theoretical luminosities and effective temperatures are translated into magnitudes and colours by means of the transformations described by Bertelli et al. (1994).

Assumed a suitable value for the metallicity Z and hence a particular set of isochrones, we derive the age τ_F from the luminosity of the youngest main-sequence stars existing in the CMDs.

Because the ratios of star counts are defined with the aid of characteristic magnitudes which are related to corresponding luminosities of the underlying evolutionary phases, a choice for the distance modulus and colour excess is needed to compare the theoretical results with the observational data. We adopt the distance modulus to the LMC $(m-M)_o=18.5$ mag of Panagia et al. (1991) and the colour excess $E_{(B-V)}=0.07$ from the maps of Schwering & Israel (1991).

4. The Results for LMC-56

The comparison of the counts in LMC-56 with their theoretical counterparts allows us to derive the following results:

No solutions exist for the law of star formation for metallicities lower than Z=0.005 and in most cases higher than Z=0.008.

No solutions are found for slopes of the IMF lower than $\varkappa=2.35$, whereas there are solutions for $\varkappa=2.85$ and $\varkappa=3.35$. However, the detailed LF of the main-sequence stars for the case $\varkappa=3.35$ does not agree with the observation. Therefore, only the case with $\varkappa=2.85$ leads to fully satisfactory results.

The age for the start of the bulk activity of star formation is significantly older than the value of 3–4 Gyrs found by Bertelli et al. (1992) for the areas NGC 1866, NGC 1783 and NGC 2155. For LMC-56 we found an age of 7–8 Gyrs.

Finally, it is worth recalling that these results do not change significantly with the distance modulus and reddening. Similar remark holds if we had adopted classical models instead of those with convective overshoot.

5. Final Remarks

Combining the results of the present study with those of Bertelli et al. (1992) and the very preliminary ones obtained for other regions of our list, there is some indication that the age of the most recent, perhaps dominant, episode of star formation has changed across the LMC. We should remind the reader that because of the adopted modelization of the SFR and the internal resolution of the method in usage, recurrent episodes of star formation cannot be singled out. What the method allows us to get is the mean age of the last, prominent episode of star formation. More detailed study is necessary before confirming whether the LMC suffered from recurrent episodes of star formation. It is tempting to attribute the LMC star bursts at 3–4 and 7–8 Gyrs to some sort of tidally induced shock caused in the past by a passage near the Galaxy, as suggested by Murai and Fujimoto (1980) and Gardiner et al. (1994).

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Geminga, 10 Years of Optical Observations

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1. Introduction

The high energy source Geminga was discovered in γ rays about 20 years ago by the NASA satellite SAS-2 (Fichtel et al., 1975); between 1975 and 1982 the source was observed several times by the ESA COS-B satellite and, in parallel, a possible X-ray counterpart (1E0630+178) was found by the EINSTEIN Observatory (Bignami et al., 1983).

The detection of Geminga at X-ray wavelengths reduced the radius of error box by a factor ~ 300. It then became possible to search for its optical counterpart. First deep inspections of the HRI error circle (r = 4″) were done with the 3.5-m CFHT (Bignami et al., 1987) and led to the observations of three possible candidates, namely stars G, G' and G″, the last one being the fainter of the three (m_V=25.5). Later observations with the ESO 3.6-m (Bignami et al., 1988) and with the 5-m Hale (Halpern and Tytler, 1988) demonstrated that the first two were quite normal field stars while the unusual colours of G″ made it the most probable candidate for the optical counterpart of Geminga.

The high energy brightness of the source coupled with its faintness in the optical (L_X/L_{opt} > 1 000) was one of the arguments which led Bignami et al. (1983) to suggest that Geminga was an isolated neutron star, in spite of the lack of detectable radio emission.

In the 1990s, GRO and ROSAT observations greatly contributed to understanding the nature of the source. First came the detection of a 237 msec. pulsation in soft X-rays (0.1–2 Kev) by ROSAT (Halpern and Holt, 1992) soon followed by a similar discovery in γ rays by EGRET (Bertsch et al., 1992). This was immediately found also in old COS-B (Bignami and Caraveo, 1992) and SAS-2 (Mattox et al., 1992) archived data. This discovery of a common periodicity confirmed the identification between the γ and X-ray source and provided important information about the nature of the object. The observed pulsation at high energies can be explained only as due to the fast rotation of a highly magnetized isolated neutron star (B ~ 1.5 10^{12} G), up to now the only one detected through its γ/X emission but quiescent at radio wavelengths.

The evolution of the period of the X/γ pulsar, computed over a time span of about 10 years (1982–1992), provided a good measure of its period derivative ($\dot{P}$ ~ 1.09 10^{-14}sec sec^{-1}) and hence of its age (about 3–10^5 years). According to the standard relation adopted for radio pulsars ($\dot{E} = I\Omega\dot{\Omega}$) the overall energy output for Geminga is ~3 10^{34} ergs sec^{-1}. Assuming that all the rotational energy of the pulsar is converted in γ rays, an upper limit for its distance can be estimated (~ 340 pc). The actual distance to Geminga is then a function of the assumed γ ray efficiency ε_γ. For an efficiency similar to that of the Vela pulsar (ε_γ ~ 0.01) a value of 30–40 pc is found.

2. The Optical Counterpart

If Geminga is, indeed, an isolated neutron star, it should move with a high tangential velocity typical of radio pulsars (~ 100 km/sec.). This, coupled with the upper limit on the distance, could lead to a measurable proper motion of the proposed optical counterpart G″ (Bignami and Caraveo, 1992). The expected proper motion can be written as:

$$\mu = 0.2 v_{100}\, d_{100}^{-1} \text{ arcsec yr}^{-1}$$

(where v_{100} is the pulsar velocity in units of 100 km sec^{-1} and d_{100} its distance in units of 100 pc). Thus, a proper motion μ = 0.2″/year should be observed for a neutron star at 100 pc travelling at 100 km/sec.

Working with images taken in 1984, 1987 and 1992, Bignami, Caraveo and Mereghetti (1992, 1993) indeed found an overall displacement to NE corresponding to a proper motion of G″ μ = 0.17″/year. This value is fully consistent with the hypothesis that G″ is a close (d < 340 pc) neutron star.

Thus, Geminga joins the restricted group of the optically identified neutron stars including PSR0531+21, PSR0833-15 and PSR0540-69, detected as pulsating sources, and PSR1509-58 and PSR0656+14 for which a likely identification was recently reported (Caraveo et al., 1994 a, b).

New V filter images of G″ have been taken in January 1994 by G.F. Bignami and P. A. Caraveo with the ESO New Technology Telescope equipped with the SUperb Seeing Imager (SUSI). In order to reduce contamination from cosmic ray hits, the whole observation was subdivided in four exposures of

TABLE 1

Date	Telescope	Filter	Pixel size	Seeing	Exp. time
1984 Jan. 7[1]	CFHT	R	0.412″	0.9″	180 min
1986 Feb. 3[2]	5m-Hale	g	0.336″	1″.8	120 min
1987 Jan. 28[3]	ESO 3.6-m	V	0.675″	1.6″	120 min
1992 Nov. 4[4]	NTT/SUSI	V	0.13″	0.6″	150 min
1994 Jan. 11[5]	NTT/SUSI	V	0.13″	1″	80 min

[1]Bignami et al. (1987); [2]Halpern and Tytler (1988); [3]Bignami, Caraveo and Paul (1988); [4]Bignami, Caraveo and Mereghetti (1992, 1993); [5]This paper.