Star clusters: basic galactic building blocks
Proceedings IAU Symposium No. 266, 2009
R. de Grijs & J. R. D. Lépine, eds.

doi:10.1017/S174392130999202X

Pre-main-sequence stars in the stellar association N 11 in the Large Magellanic Cloud: clustering properties

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Abstract. Magellanic Clouds are of extreme importance to study the star-formation process in low-metallicity environments. Here, we discuss the clustering properties of the pre-main-sequence candidates and young embedded stellar objects in N 11, located in the Large Magellanic Cloud. Deep archival *HST*/ACS photometry is used to derive color–magnitude diagrams of the associations in N 11 and of the foreground field population. These data are complemented by archival infrared *Spitzer* data which allow detection of young embedded stellar objects. The spatial distribution of the pre-main-sequence candidates and young embedded stellar objects is discussed. The degree of clustering is derived using the minimal-spanning-tree method. No significant difference is found in clustering degree of young blue main-sequence stars and faint pre-main-sequence candidates, suggesting that they might be part of the same formation process.

Keywords. Magellanic Clouds, stars: pre–main-sequence, stars: formation

1. Introduction

The Magellanic Clouds are ideal laboratories to study the process of star formation in detail owing to their proximity. In the Large Magellanic Cloud (LMC), several regions of active star formation are found. N 11 is the second largest nebula in the LMC after the 30 Doradus nebula. It is located in the north-western corner of the LMC. Bica *et al.*'s (1999) catalog lists 49 clusters and associations in the entire region of N 11. In the ares studied, about 13 objects are found (see Figure 1). This region is often presented as one of the best examples of triggered star formation (Mokiem *et al.* 2007). The basic idea is that the association LH 9 has triggered star formation in LH 10 and LH 13. Here, we make use of *HST* ACS/WFC archival data complemented by *Spitzer* archival data (SAGE project; Meixner *et al.* 2006). While *HST* observations can provide information about faint, exposed pre-main-sequence candidates (PMSs), infrared data allow to detect embedded young stellar objects (YSOs). This paper is part of a project aiming to cast light on the process of field and cluster star formation in the Magellanic Clouds (see, among others, Chiosi & Vallenari 2006, 2007).

2. PMS detection in N 11

A large population of pre-main-sequence candidates is found in N 11. Their masses are in the range 1.3–2 $M_\odot$ and they are compatible with having ages from 2 to 10 Myr. YSOs with ages between 0.1 and 1 Myr are found intermixed with PMSs. More details can be found in Vallenari (2008) and Vallenari *et al.* (2009). Here, we summarize the most relevant results.

2.1. *Age determination*

Our analysis of the *HST* data implies that PMSs in LH 9 are slightly older than elsewhere in N 11. Prolonged star formation is detected in LH 9 South, with ages from 2 to 10 Myr, while LH 9 North, LH 10 (center) and LH 13 seem to be younger (with mean ages of 5, 2 and 2 Myr, respectively). A large age spread from 1 to 6 Myr is found based on spectroscopy of blue stars in these regions. The presence of YSOs in LH 9 South, LH 13 (type I, with ages < 0.1 Myr) and LH 9 (North), LH 10 (Type II, ages $< 1 - 2$ Myr) suggests that star formation in the region is still ongoing. Mokiem *et al.* (2007) estimate that the time needed for a supernova shock to cross the distance between LH 9 and LH 10 is on the order of 0.1 Myr. Since the lifetime of massive stars is on the order of 3 Myr, the age difference is in agreement with the idea that LH 9 has triggered the formation of a first stellar generation in LH 10. This cannot be excluded on the basis of our discussion, even if more generations of stars are found in the region.

2.2. *Spatial distribution*

We compare the location of PMS candidates selected on the basis of ACS photometry with the Hα-emission map of Mac Low *et al.* (1998), with the CO cloud distribution (Israel *et al.* 2003) and with Herbig Ae/Be-star concentrations (Hatano *et al.* 2006). The most conspicuous concentrations of PMSs correspond to the locations of OB stars. As for Herbig Ae/Be stars, they are found in all these locations, confirming the presence of a population with ages in the range of 1–3 Myr (see Figure 1). YSOs are found inside or close to the CO clouds.

3. Clustering properties of the PMSs and the field population

Interstellar turbulence is found to be very efficient in sweeping up molecular gas forming massive structures, which in turn can undergo a large-scale gravitational collapse. As a consequence, clusters are formed in a hierarchical fashion with subclusters which eventually merge to build up the final, condensed object (Schmeja *et al.* 2009). For this reason, the clustering properties of the stars in a region can provide information about the formation and evolution of the stellar structures. A powerful method used in the literature for statistical analysis of the spatial distribution of the stars in a cluster is the minimal spanning tree (MST). The MST is the unique network of straight lines joining a set of points such that it minimizes the total length of all lines without creating closed loops. Schmeja & Klessen (2006) demonstrate that the structure of a cluster can be derived using the parameter $Q = m/s$, comparing the mean length, m, of its MST to the normalized correlation length, s, defined as the mean separation between the stars. Table 1 shows the Q values for the region studied. In all N 11 fields, the values of $Q < 0.8$ are typical of the products of hierarchical star formation. Different clusters/associations have slightly different values of Q, suggesting that they might be at slightly different evolutionary stages. Q is found to be independent of the age of the clusters. This result is not in agreement with the behavior found in Galactic star-forming regions (Schmeja *et al.* 2009). These results are quite difficult to interpret. They can be explained as the footprints of inhomogeneity in the original turbulent cloud. However, it should be kept in mind that this comparison is complicated by the presence of a large age dispersion detected in the fields.

Inside N 11, no significant difference is found in the clustering degree of brighter blue main-sequence stars ($m_{\rm F435W} < 20$ mag) and fainter red stars ($m_{\rm F435W} > 20$ mag), suggesting that they might be part of the same formation process.

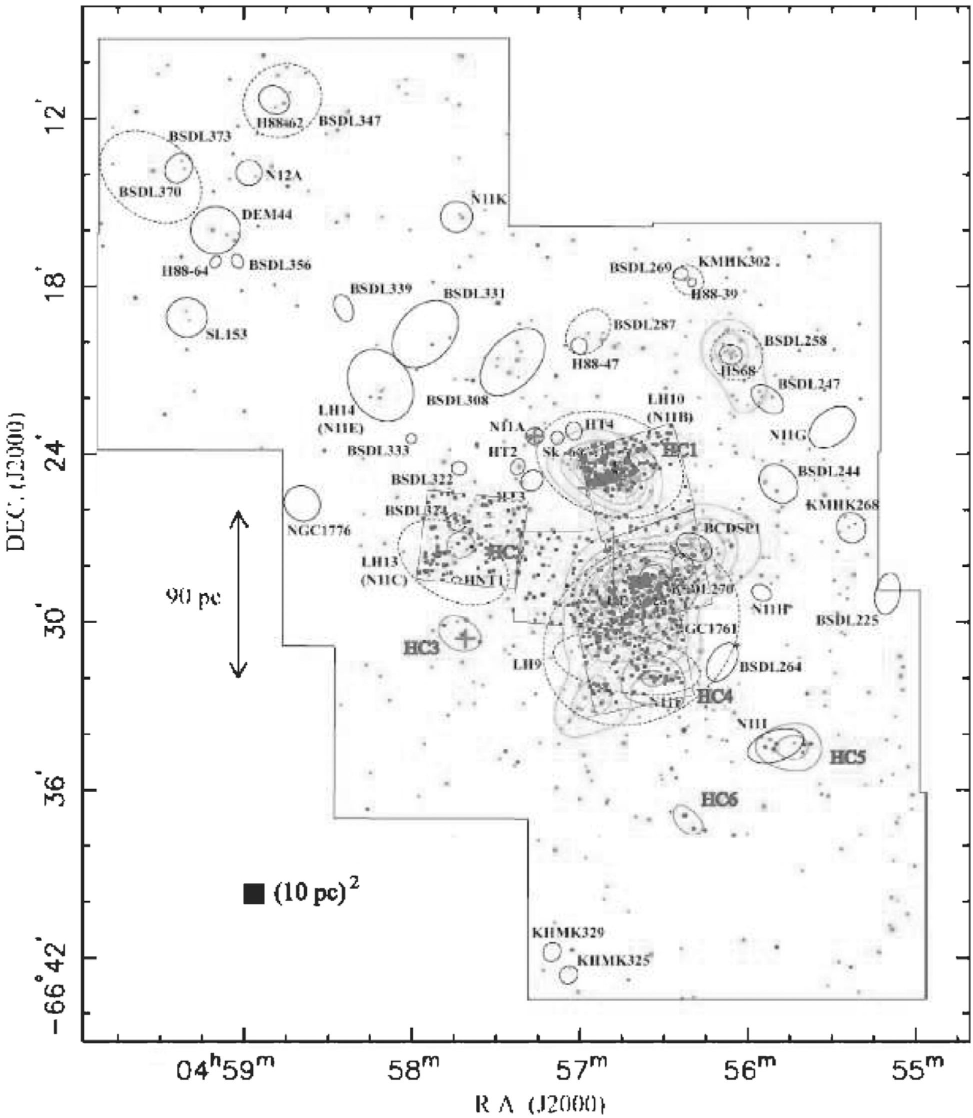

Figure 1. Map of N 11, where the clusters/associations from Bica et al.'s (1999) catalog are indicated. Red circles (marked HC1 to HC6) and cyan contours show the Herbig Ae/Be and OB candidates, respectively (from Hatano *et al.* 2006). Large boxes show the ACS/WFC fields studied in this paper. Small red dots show the PMS candidates selected on the basis of ACS photometry.

4. Conclusions

In this paper, we discuss the formation process of clusters and stars in N 11, and analyze the age and the clustering properties of the clusters/associations found in the region.

PMS and YSO candidates associated with N 11 are discovered based on *HST* ACS/WFC photometry and archival *Spitzer* data. While *HST* observations can provide information about faint, exposed pre-main-sequence candidates, infrared data allow us to detect embedded young stellar objects.

PMSs have masses from 1.3 to 2.0 $M_\odot$. Their ages range from 2 to 10 Myr. LH 9 PMSs are older than the objects in the other associations. YSOs (types I and II) with ages < 1 Myr and Herbig Ae/Be stars with ages in the range 1–3 Myr are found in the same locations as the PMSs.

The degree of clustering of the stars is discussed to get clues about the formation process. PMSs exhibit a higher degree of clustering in comparison with the full stellar sample. For all clusters/associations in N 11, the values of $Q \leqslant 0.8$ indicate hierarchical star formation. In turbulent regimes, it is expected that the clusters evolve from hierarchical structures towards more concentrated configurations. This behavior is not found in the region studied, where Q shows no age dependence. This might reflect inhomogeneity in the original turbulent cloud.

Table 1. Q values for all stars in the cluster areas given by Bica *et al.*

Object	$\bar{m}$	$\bar{s}$	Q
NGC 1769	0.86	1.33	0.65
NGC 1763	0.73	0.98	0.75
NGC 1761	0.77	1.18	0.66
NGC 1760	0.73	1.20	0.56
HD 32228	0.73	0.93	0.79
BSDL 324	0.80	1.11	0.73
BSDL 270	2.45	3.64	0.67
BCDSP 1	0.78	1.19	0.66

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