The dense molecular clump at the center of the Barnard 59 (B59) complex is the only region in the Pipe Nebula that has formed a small, stellar cluster. The previous analysis of a high-resolution near-IR dust extinction map revealed that the nuclear region in B59 is a massive, mostly quiescent clump of $18.9 \ M_\odot$. The clump shows a monolithic profile, possibly indicating that the clump is on the way to collapse, with no evident fragmentation that could lead to another group of star systems. In this paper, we present new analysis that compares the dust extinction map with a new dust emission radio-continuum map of higher spatial resolution. We confirm that the clump does not show any significant evidence for prestellar fragmentation at scales smaller than those probed previously.

**Key words:** infrared: ISM – ISM: clouds – radio continuum: ISM – radio lines: ISM – stars: formation

**Online-only material:** color figure

1. INTRODUCTION

The formation of a stellar cluster proceeds when a molecular cloud clump hosts multiple dense fragments capable of collapsing independently. Cluster-forming clumps populate the high-end bins of the mass and density distributions in a cloud (Williams et al. 1995; Di Francesco et al. 2010), but very few details are known about the process of fragmentation, since cluster-forming clumps in very early stages of evolution are relatively rare.

The recently popular Pipe Nebula (see Alves et al. 2008b and references therein) has become a prototype case for a cloud in a very early stage of evolution. The Pipe Nebula hosts only one star-cluster-forming clump, Barnard 59 (B59), and one core hosting a single young source in a nearby filament (Forbrich et al. 2009). The rest of the cloud contains more than 130 starless cores that resemble stars in the way their masses are distributed (Alves et al. 2007; Rathborne et al. 2009) and how they are distributed spatially (Román-Zúñiga et al. 2010). Dense cores in the Pipe appear to be still mostly quiescent and stable against collapse (Lada et al. 2008), despite some of them being already chemically evolved (Frau et al. 2010; Frau et al. 2011a, 2011b). Currently, the best candidate for a mechanism that supports cores in the Pipe against collapse is the magnetic field that appears to permeate the cloud (Alves et al. 2008a; Franco et al. 2010).

The B59 complex hosts one of the less massive and less distant ($d = 130$ pc) young stellar clusters observable. During the last 2.6 Myr, B59 has formed 14 stars, all below $3 \ M_\odot$ (Covey et al. 2010, hereafter CLR10). The analysis of a high-resolution ($24''$) near-infrared dust extinction map of the B59 region (Román-Zúñiga et al. 2009, hereafter RLA09) revealed that B59 is a complex group of dense cores and filamentary structures, in which the central clump, B59-09, hosts most of the cluster members. The analysis of the dust extinction map suggests that the central clump has a smooth profile that compares well with that of an isothermal sphere, with no evidence of internal fragmentation. Moreover, pointed NH$_3$ observations inside the core show that the thermal-to-non-thermal kinetic energy ratio averages well over unity, suggesting that B59-09 remains mostly quiescent despite having formed a star cluster. The main goal of this study is to confirm such a scenario by showing that a radio continuum dust emission map with higher spatial resolution also lacks evidence for fragmentation in the central core.

The paper is divided as follows: in Section 2, we describe the observations and data reduction process. Our results are detailed in Section 3 and, to conclude, we elaborate a discussion about their significance in Section 4.

2. OBSERVATIONS

2.1. MAMBO-II

We mapped B59 at 1.2 mm (250 GHz) with the MAMBO-II bolometer at the 30 m IRAM telescope atop Sierra Nevada (Spain). MAMBO-II features a 117-receiver array that covers $11''$ in diameter. The observations were carried out in 2009 November in the framework of a flexible observing pool. The weather conditions were good and zenith optical depth remained within 0.1–0.3. A total of five usable on-the-fly maps were completed and combined. The beam size of the telescope is $11''$ at the effective frequency of 250 GHz; we used a constant scanning at a speed of $8''$ s$^{-1}$ in the azimuthal direction for up to 65 s. This strategy resulted in average integration times per map of $\sim 1$ hr. Each map was performed with a different secondary chopping, which varied between $30''$ and $80''$, parallel to the scanning direction of the telescope. This procedure assured that we had a different OFF position for each ON position within the map. The scanning direction was also changed for each map, giving a different zero emission level, which helped to avoid spatial filtering effects. The zenith optical depth was measured with a skydip at the start and end of a map. Pointing and focus were checked also at the start and end of a map, with corrections below $3''$ and 0.2 mm, respectively. Flux density calibrators were observed every few hours. The data reduction was done with standardized routines from MOPSIC software included in the GILDAS package.

4 GILDAS and MOPSIC are available at http://www.iram.fr/IRAMFR/GILDAS.
2.2. Near-infrared Dust Extinction Map and Additional Radio Data

We make use of the dust extinction map of RLA09 constructed with the NICER technique (Lombardi & Alves 2001) and a combined photometric catalog obtained from ground (ESO) and space-based (Spitzer) observations. In addition to the infrared data, we also make use of a series of pointed observations made with the Green Bank 100 m telescope to determine the variation of the emission of the (1,1) and (2,2) rotation–inversion transitions of ammonia (NH$_3$) across the central clump B59-09. These data were also used and described in RLA09. Finally, we also make use of a C$^{18}$O (2–1) line emission map obtained with the detector HERA at the IRAM 30 m telescope (C. G. Román-Zúñiga et al., in preparation).

3. DATA ANALYSIS AND RESULTS

In the top panel of Figure 1, we show our MAMBO-II map toward B59. The map detected mostly the emission from the clump 09ab$^5$ and, less prominently, the core 09c at the northwestern end. Five young stellar objects were detected with very high signal-to-noise ratios (S/Ns). They correspond to sources 6, 7, 9, 10, and 11 in the list of (Brooke et al. 2007, hereafter BHB07). The 250 GHz continuum emission properties of these sources are listed in Table 1. Note that sources BHB07-6 and BHB07-7 lie very close together and they are not resolved as separated sources in the MAMBO-II map. As our main purpose is to study the emission of the core, we subtracted out the contribution of the young stars. For this purpose, a two-dimensional Gaussian profile was fit to each of the sources, using a background emission level corresponding to the average in the vicinity region of the clump. The fit parameters are listed in Table 1. The smoothness of the resulting map (see the central panel in Figure 1) seems to confirm that most of the subtracted emission arises from the YSO warm circumstellar material rather than from the core cold dust.

After subtracting the contribution from the YSOs, we transformed the dust emission maps to column density and then into visual extinction for a direct comparison with the NICER map of RLA09. The conversion was done following the method described in Section 4.1 and Appendix A of Frau et al. (2010). We note that the conversion is very sensitive to the assumed value for gas temperature, $T_k$ (see Appendix 1 of Frau et al. 2010), and also the dust emissivity ($\kappa_\nu$) and the dust temperature assumed. Following Ossenkopf & Henning (1994), we assumed $\kappa_\nu = 0.007$ cm$^2$ g$^{-1}$ for grains in a dense medium ($n \sim 10^5$ cm$^{-3}$). Then, we computed visual extinction maps for gas/dust temperatures in the 10–12 K range in steps of 0.25 K (ammonia observations yield $T_k = 11.3 \pm 0.7$ K; Rathborne et al. 2009). We selected a temperature of 10.25 K as this value showed the best agreement with respect to the previous extinction map, and we made the assumption that this temperature is constant within the entire clump. The derived radius, mass, and average density of the clump are listed in Table 2. Given the high S/N achieved, we restricted analysis to the region satisfying $I_\nu > 0.2I_{\nu, \text{max}}$ ($\sim 4.5\sigma$). The total mass of the clump 09ab in B59 estimated from the MAMBO-II map is about half of that estimated from the NICER map (i.e., cores 09ab and 09c sum about 21 $M_\odot$ according to RLA09). This difference is mostly because MAMBO-II maps are not as sensitive as the near-infrared excess method in detecting the diffuse gas at the

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$^5$ We follow the nomenclature of RLA09, see their Table 1.
external parts of dense cores ($A_V < 25$ mag in this case), rather than a technical effect. The partial detection of cores 09cd and 04a seems to confirm the good quality of the emission maps despite their lack of sensitivity. The NICER technique relies on having enough sources per beam to average reddening, and despite their lack of sensitivity. The NICER technique relies on having enough sources per beam to average reddening, and the assumption of a constant temperature (other than a technical effect). Also, the assumption of a constant temperature for the entire region is less accurate toward the core boundaries that might be heated by external sources.

Morphologically, the MAMBO-II dust extinction map shows features that are equivalent features to those found in the NICER map of RLA09, which is shown in the bottom panel of Figure 1. Both maps show a relatively flat central region toward the clump 09ab with a shallow “dent” near the location of source BHB07-10, discussed in Section 5.1 of RLA09. A radial profile of the MAMBO-II map was constructed by averaging flux in circular, concentric rings centered on J2000 ($\alpha, \delta$) = (17:11:23.0, -27:25:59.3), as in RLA09. Figure 2 shows that observed profiles compare well with each other and trace equivalent structures within $\sim 10^4$ AU ($A_V > 35$ mag). Below $A_V \approx 35$ mag, the MAMBO profile plunges and appears to be truncated below an average radius of $2 \times 10^3$ AU, while the NICER profile continues until it reaches the background level near $5 \times 10^4$ AU.

We used our pointed NH$_3$ observations (RLA09) and the C$^{18}$O(2–1) map to categorize the variation of the LSR velocity near the center of the clump. Twelve NH$_3$ pointed observations were made within the central $10^4$ AU of B59. All of them indicate variations of $v_{LSR}$ smaller than $0.088$ km s$^{-1}$ from the central value of $3.485$ km s$^{-1}$. Moreover, these variations are below the average velocity dispersion ($\sigma_v$) = $0.210 \pm 0.0498$ km s$^{-1}$ and below the sound speed in a 10 K gas ($c_s$ = $0.12$ km s$^{-1}$). The C$^{18}$O (2–1) map reveals variations below $0.05$ km s$^{-1}$ from the central velocity value. The linewidths, although being significantly wider than those of the NH$_3$, also show very small variations (less than $0.08$ km s$^{-1}$) from the average value of $0.87$ km s$^{-1}$, indicating very uniform kinematics near the center of B59-09ab. Rathborne et al. (2009) discussed how kinematically independent cores in the Pipe Nebula must show radial velocity differences larger than $c_s$. 

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**Table 1**

Properties of YSOs Counterparts

| ID$^a$   | Class$^a$ | Spectral Type$^b$ | Peak Flux (mJy beam$^{-1}$) | Mass$^b$ ($M_\odot$) | $\Delta\alpha$, $\Delta\delta$ (°) | Deconvolved Size$^d$ (°, deg) |
|----------|-----------|-------------------|------------------------------|-----------------------|----------------------------------|---------------------------------|
| BHB07-11 | I         | ⋯                 | 270.0                        | ⋯                     | $-11.0$, 55.5                    | $18.0 \times 17.0$, $-68.0$      |
| BHB07-10 | 0/I       | ⋯                 | 65.0                         | ⋯                     | $65.0$, $-24.0$                  | $16.0 \times 16.0$, $0.0$        |
| BHB07-09 | Flat      | K5                | 115.0                        | 0.77–0.79             | $-29.4$, $-133.0$               | $13.7 \times 12.1$, $-89.5$      |
| BHB07-06 | II        | M2                | 15.0                         | 0.24–0.62             | $15.0$, $-80.0$                 | $14.0 \times 12.0$, $79.4$       |
| BHB07-07 | Flat      | K5                | 15.0                         | 0.75–1.16             | $15.0$, $-80.0$                 | $14.0 \times 12.0$, $79.4$       |

**Notes.**

$^a$ From Brooke et al. (2007).

$^b$ From Covey et al. (2010).

$^c$ Offsets from center of map at ($\alpha, \delta$) = (17:11:23.0, -27:25:30.0).

$^d$ Indicates major and minor axes, and position angle.

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**Table 2**

Barnard 59: Dust Emission Map

| Parameter | Value |
|-----------|-------|
| $T_e$     | 10.25 K |
| rms       | 4 mJy beam$^{-1}$ |
| Total flux | 8.28 Jy |
| Peak flux | 90.7 mJy beam$^{-1}$ |
| Diameter$^b$ | 0.11 pc |
| $N_{H_2}$ $^c$ | $2.96 \times 10^{22}$ cm$^{-2}$ |
| $n_{H_2}$ $^c$ | $1.30 \times 10^{7}$ cm$^{-3}$ |
| Mass      | 9.19 $M_\odot$ |

**Notes.**

$^a$ Corresponds to our best fit to the $A_V$ profile, not to a measured value.

$^b$ Size of region with emission above $I_v > 0.2I_{v,\text{max}}$.

$^c$ Average value over region with emission above $I_v > 0.2I_{v,\text{max}}$.

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Figure 2. Open circle symbols show the radial profile of the NICER extinction map. The black diamond symbols show the radial profile of the MAMBO-II dust emission map. The profiles were constructed by averaging flux in circular, concentric rings centered on J2000 ($\alpha, \delta$) = (17:11:23.0, -27:25:59.3). For the MAMBO-II profile, the data were convolved to the resolution of the NICER map (20") and re-gridded to match pixels in both maps.
Following this prescription, the differences we observe are too small to suggest the presence of kinematically independent substructure.

4. DISCUSSION

The radio continuum map has twice the resolution of the NICER map (11″ FWHM beam versus 24″ FWHM Gaussian filter), resolving a projected size of 1420 AU (assuming a distance of 130 pc to the Pipe Nebula). We could safely say that the MAMBO-II map should resolve structures with minimum sizes of 2000–5000 AU. Our map, however, does not reveal any significant substructure (other than the sources or the dent) below ~1.5 × 10^4 AU. This result is in good agreement with those of Román-Zúñiga et al. (2010), who reported a possible limiting scale of fragmentation in the Pipe Nebula of about 1.4 × 10^4 AU. As also noted there, this scale agrees with the results of Schnee et al. (2010) who found no evidence of fragmentation in cores of the Perseus Molecular Cloud at scales of 10^3–10^4 AU.

The column density estimates made from near-IR extinction and dust emission are very similar near the center. Both maps fail to show evidence of substructure suggestive of significant fragmentation in B99ab. The dust emission map confirms that the dent is real and thus it suggests that source BHB07-10 is possibly affecting the material surrounding it. The decrement of column density near source BHB07-10, however, is equivalent to a decrement of only 3% in the total mass of the clump (RLA09). Also, CLR10 showed that BHB07-10 is not embedded at the level at which it is projected against the map. In contrast, source BHB07-11 has been suggested to be the origin of a moderate gas outflow (Onishi et al. 1999) that seems to be carving the northern part of the clump, forming core 09c. Thus, the feedback effect near BHB07-10 may not account for a bona fide fragmentation process as in core 09c.

The young stellar cluster in B59 is likely too small to hold itself together dynamically. Following Adams & Myers (2001), for the B59 cluster to remain stable, its relaxation timescale, t_{rlx}, should be at least larger than its formation timescale, which in turn should be comparable to the age of the cluster. The age of the B59 cluster is estimated as being 2–3 Myr (CLR10). The relaxation parameter, Q_{rlx}, i.e., the number of crossings per relaxation time, can be estimated in terms of the star-forming efficiency, ϵ, and the number of stars, N⋆, as N⋆/(10^2 ϵ ln(N⋆/ϵ)). Using the present-day value, ϵ = 0.3 (CLR10) and, for 10 sources projected within B59-09ab, we obtain Q_{rlx} = 3.2. Therefore, given the crossing time of the clump, t_{cr} ≈ 0.06 Myr, then t_{rlx} = Q_{rlx}t_{cr} ≈ 0.2 Myr, which is much shorter than its formation time. It is thus very unlikely that the B59 stellar cluster will remain together longer than a few more crossing times.

Experimental fits of isothermal sphere profiles, particularly Bonnor–Ebert and Dapp & Basu (2009) to the NICER profile, suggest that the core is already out of equilibrium, although it is not possible to estimate its state of evolution toward collapse (see also RLA09). The velocity dispersion from the NH3 data and the parameters from Table 2 yield a virial parameter value α_{vir} = 0.25, which suggests that the B59-09ab clump is gravitationally bound. Thus, we should expect the clump to be presently moving toward collapse. As shown in RLA09, B59-09ab remains mostly quiescent. Moreover, our data show that the clump has been able to amass between 9 M⊙ and 19 M⊙ of gas (the latter if we consider the whole dust extinction structure) in an apparently monolithic structure, and we know from the age of the cluster that the period of mass aggregation could be as long as about six crossing times long (CRL10). What is the mechanism that held the clump together, retarding collapse and fragmentation for a relatively long period?

Feedback in the form of outflows could serve as a turbulent energy injection mechanism that could provide the non-thermal support required to maintain the clump against collapse. Several authors have provided evidence of one and possibly two outflows from embedded sources BHB07-09 and BHB07-11 (Onishi et al. 1999; Brooke et al. 2007; Riaz et al. 2009), and RLA09 discussed how these could be carving structures at the outer regions of the clump. The presence of at least four YSOs located at projected distances larger than the Jeans length of the core (see below) could suggest that B59-09ab is more likely a remnant of dense gas after an episode of multiple source formation within a much larger structure. Even source BHB07-10 could also be affecting the core at a shallow level, as discussed above. The numerical experiments of Krumholz et al. (2007) and Offner et al. (2010) have shown that radiative feedback can be a strong agent against fragmentation. For instance, feedback from protostars can inhibit the formation of binaries in a fragmenting disk scenario. These models, however, require stars with masses above 3 M⊙ and the mechanisms work best at spatial scales about one order of magnitude smaller than the observed size of B59. Since sources in B59 have too low of masses and are not numerous, it is thus very unlikely that they can either provide non-thermal support against collapse or do not provide enough feedback energy to inhibit fragmentation (see, e.g., Longmore et al. 2010).

The other plausible candidate for a mechanism that can prevent further collapse and fragmentation of cores in B59 (as well as other regions of the Pipe Nebula) is the magnetic field. Numerical studies like those of Nakamura & Li (2011) concluded that for an initially magnetically subcritical cloud, a strong magnetic field is able to slow down gravitational collapse and fragmentation, decreasing the star formation rate significantly. Also, Price & Bate (2007) showed that support by magnetic fields may deter density perturbations and the fragmentation of disks in the case of binary formation. The optical polarization studies of Alves et al. (2008a) and Franco et al. (2010) strongly suggest that the Pipe is permeated by a magnetic field. Moreover, Frau et al. (2010) have shown that chemically evolved cores in the Pipe are possibly associated with a strong magnetic field, which is suggestive of significant magnetic support.

Following the formulation of Mouschovias (1991), we find a Jeans length scale of λ_{J,ex} = 0.12 pc, which is about twice as large as the radius of the clump in the dust emission map, within which have demonstrated the monolithic behavior of the clump (although this length is very close to the radius estimated from the dust extinction map). The data of Franco et al. (2010) indicate that B59 may be sub-Alfvénic, so in the overall region the magnetic field is dynamically more important than the turbulence.

From the Jeans length scale and the critical magnetic length scale, λ_{M} = 0.91(B/μG)^2(1 × 10^3 cm^{-3}/n) (Mouschovias 1991), and considering both the visual extinction and dust emission map derived values of the clump radius, we can infer that a magnetic field strength in the range of 0.1–0.2 mG would be enough to support the clump. These values are larger than those calculated from optical polarization data of the diffuse surrounding gas. However, magnetic field is expected to strengthen toward denser regions as the collapse process evolves.
(e.g., Fiedler & Mouschovias 1993) and these estimates are not unreasonable compared to other dense cores (see Crutcher 1999; Crutcher et al. 2004).

While the profile of B59 suggests that the core is out of equilibrium (C. G. Román-Zúñiga et al., in preparation), our continuum map shows that it has not finished collapse for a time comparable to the age of the stellar cluster. Magnetic field support (or an equivalent combination of supporting mechanisms) could have been active during such a timescale. The age of the cluster suggests that B59-09ab has survived for a period longer than 10 $t_f$ without completely collapsing or fragmenting, and it is unlikely that it will fail to evolve toward protostellar collapse. Experiments by Galván-Madrid et al. (2007) suggest that pre-stellar core survival can be assured for at most 3–10 $t_f$ for cores with densities above $10^5$ cm$^{-3}$, independently of mass to magnetic flux ratio. Despite the lack of fragmentation in B59-09ab at present, we cannot assure from our data only that the clump will not fragment later. We think, however, that further fragmentation is unlikely because fragmentation tends to proceed quite rapidly. For instance, some numerical studies, like those of Boss (2009), show that oblate cores with magnetic fields can form binaries in timescales of less than 2–4 $t_f$. Also, the models of Price & Bate (2009) show that fragmentation in a core with initial mass of 50 $M_\odot$ and initial radius of 0.375 pc—possibly not that much different from a low-mass star-cluster-forming core like B59—proceeds within 1–2 $t_f$ independently of the amount of magnetic and radiative feedback support added to their models.

Our analysis confirms the hypothesis that B59-09ab does not show significant fragmentation at the present time. We speculate that the clump is likely on its way to collapse, but it will not form multiple sources to increase the population of the small stellar cluster. The efficiency of formation in the cluster B59 after the collapse of the B59-09 clump will increase only modestly. B59 probably will remain as a small, low-mass star cluster with too few stars to survive disintegration by evaporation (Lada & Lada 2003).

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