Pre-main sequence stars in LH 91

R. Carini¹, K. Biazzo¹, G. De Marchi², N. Panagia³, G. Beccari⁴, and E. Brocato¹,⁵

¹ INAF-Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monte Porzio Catone (RM), Italy
² European Space Research and Technology Centre, Keplerlaan 1 2200 AG Noordwijk, Netherlands
³ Space Telescope Science Institute 3700 San Martin Drive, Baltimore MD 21218, USA
⁴ European Southern Observatory Karl-Schwarzschild-Str.2, 85748 Garching, Germany
⁵ INAF-Osservatorio Astronomico d’Abruzzo, Via Mentore Maggini, s.n.c., 64100 Teramo, Italy

don’t principally nearby star-forming regions (ground-based telescopes, these methods can be applied to relatively nearby star-forming regions), because of crowding. For this reason, the properties of low-metallicity PMS stars located in extra-galactic star-forming regions remain poorly known.

ABSTRACT

Aims. We study the accretion properties of pre-main sequence (PMS) low-mass stars in the LH 91 association within the Large Magellanic Clouds.

Methods. Using optical multiband photometry obtained with the Hubble Space Telescope, we identify 75 candidates showing Hα excess emission above the 3σ level with equivalent width EW_{H\alpha} > 10 Å. We estimate the physical parameters (effective temperature, luminosity, age, mass, accretion luminosity, and mass accretion rate) of the PMS stellar candidates.

Results. The age distribution suggests a period of active star formation ranging from a few million years up to ~ 60 Myr with a gap between ~ 5 Myr and 10 Myr. The masses of the PMS candidates span from 0.2 M\odot for the cooler objects to 1.0 M\odot with a median of ~ 0.80 M\odot. The median value of the accretion luminosity of our 75 PMS stars is about 0.12 L\odot, the median value of the mass accretion rate is about 4.8 × 10^{-9} M\odot yr^{-1} with higher values for the younger population (~ 1.2 × 10^{-9} M\odot yr^{-1}), and lower values for the older candidates (~ 4.7 × 10^{-9} M\odot yr^{-1}). We compare our results with findings for LH 95, the closest region to LH 91 for which accretion properties of PMS candidates were previously derived. An interesting qualitative outcome is that LH 91 seems to be in a more evolved stage. Moreover, we find that the PMS candidates are distributed homogeneously, without any evidence of clumps around more massive stars.

Conclusions.

Key words. Accretion, accretion disks—Stars: pre-main sequence—Stars: formation—Galaxy: Magellanic Clouds—open clusters and associations: individual: LH 91—Techniques: photometric

1. Introduction

In the magnetospheric accretion scenario, the accretion of material from a circumstellar disk in low-mass pre-main sequence (PMS) stars is funneled by the stellar magnetic field, which disrupts the disk at a few stellar radii (Hartmann et al. 2016, and reference therein). Our understanding of this process is still not entirely clear. A key parameter describing the star–disk evolution is the rate of mass accretion, that is, the rate at which mass from the circumstellar disk is transferred onto the central PMS star (see, e.g., review by Hartmann et al. 2016). In particular, it is important to evaluate the relation between mass accretion rate, stellar mass, and age, how the mass accretion rate changes as a star approaches its main sequence (MS), and how the metallicity or in general the chemical composition of the parent molecular cloud could impact the formation and evolution of the star.

Usually, mass accretion rates are derived from the analysis of continuum veiling, ultraviolet (UV) excess emission, or indeed through a detailed study of the profile and intensity of hydrogen emission lines (e.g., Hα, Paβ, Brγ), which requires medium- to high-resolution spectroscopy for each individual object. Even with modern multi-object spectrographs at the largest ground-based telescopes, these methods can be applied to relatively nearby star-forming regions (d < 1 – 2 kpc), because of crowding. For this reason, the properties of low-metallicity PMS stars located in extra-galactic star-forming regions remain poorly known.

In the last decade, De Marchi et al. (2010) developed an efficient method based on Hubble Space Telescope (HST) photometry that allows the identification of hundreds of PMS stars simultaneously, and the determination of their physical parameters, including effective temperature, luminosity, age, mass, Hα luminosity, accretion luminosity, and mass accretion rate, with an uncertainty of between 15% and 20%, comparable to that allowed by spectroscopy.

This method has been successfully applied not only to regions of the Milky Way (Beccari et al. 2010, 2015; Zeidler et al. 2016), but also to regions of the Small (De Marchi et al. 2011, 2013) and Large Magellanic Clouds (e.g., Biazzo et al. 2019, De Marchi et al. 2017, Spezzi et al. 2012). This method combines V (F555W) and I (F814W) broadband photometry with narrow-band Hα (F656N or F658N) imaging to identify the stars with excess in Hα emission and to determine their associated Hα emission equivalent width, EW_{H\alpha}, the Hα luminosity and the accretion properties of the PMS stars selected.

In this work, we use this method to select and study the PMS populations of the stellar system LH 91 (Lucke 1974) in the northeast outer edge of the super-giant shell LMC 4 in the Large Magellanic Cloud (LMC). This area, investigated with Hα and radio observations by Book et al. (2009), also covers LH 91 I in the southeast of LH 91 (Kontizas et al. 1994) and LH 95 in the north of LH 91 (Lucke 1974).

The most recent work on LH 91 was presented by Gouliermis et al. (2002) using ground-based BVR and Hα photometry.

©ESO 2022

April 4, 2022

Article published by EDP Sciences, to be cited as https://doi.org/10.1051/0004-6361/202243118
Table 1. Logbook of the observations

<table>
<thead>
<tr>
<th>Camera</th>
<th>Number of exposures</th>
<th>Filter</th>
<th>Exposure time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>(s)</td>
</tr>
<tr>
<td>Prop ID 12872, PI: Da Rio</td>
<td>WFC3</td>
<td>1</td>
<td>2804</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>2970</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2804 + 2970</td>
</tr>
<tr>
<td>Prop ID 13009, PI: De Marchi</td>
<td>WFC3</td>
<td>1</td>
<td>2949</td>
</tr>
</tbody>
</table>

Studying the Hα topography of the area, the authors found that LH 91 is loosely related to an H α region, which seems to be large and rather diffuse. In agreement with Lucke (1974), the authors confirm that LH 91 does not seem to represent a "classical" stellar system in which the stars are physically related to each other. Analyzing the color–magnitude diagram (CMD) in the B and V bands, the authors estimated the color excess $E(B-V) = 0.16 \pm 0.04$ using the reddening-free Wesenheit function. Moreover, fitting the Geneva isochrones (Schaerer et al. 1993) derived adopting metallicity $Z=0.008$, Gouliermis et al. (2002) derived the age of the system, finding it to be younger than 10 Myr, similar to that of LH 95 and LH 97I, and in agreement with for example Braun et al. (1997, 2000). Instead, Kontizas et al. (1994) estimated an age of about 20 Myr. Finally, Gouliermis et al. (2002) also estimated the age of the background field, the population of the observed area around LH 91, to be older than 50 Myr and up to 1.25 Gyr.

This paper is organized as follows: in Section 2 we describe the analysis needed to identify the PMS stars and to estimate the luminosity and the equivalent width (EW) associated to the Hα excess. In Section 4 we measure the physical properties of the stars selected. In Section 5 we determine the accretion properties of the selected PMS stars, that is, the accretion luminosity and mass accretion rate, and we show the relation between the mass accretion rate and the stellar properties of the PMS objects, such as their mass and age. We also compare our results with the findings for other star-forming regions in the LMC with the same chemical and physical parameters appropriate for the LMC (effective temperature $T_{\text{eff}}$ in the range of 3500–40000 K, surface gravity $\log g = 4.5$, and metallicity index $[M/H] = -0.5$, Colucci et al. 2012). The agreement between our reference sequence and the theoretical one is evident at $m_{\text{F555W}} - m_{\text{F814W}} < 1$. The discrepancy between the models and the data at $m_{\text{F555W}} - m_{\text{F814W}} > 1$ can be attributed to small number statistics and to the fact that the majority of these objects are red giants, with different physical characteristics from those assumed in the models.

3. Data analysis

3.1. PMS star identification

We applied the method developed by De Marchi et al. (2010) to identify the PMS stars characterized by an active mass accretion process. We measured the physical and accretion properties of these objects (i.e., Hα luminosity, Hα emission EW), mass accretion rate, and accretion luminosity) using photometric data. We refer to De Marchi et al. (2010) for a detailed discussion of the method, while in this work we describe some fundamental steps.

We selected PMS stars on the basis of their Hα excess emission (White & Basri 2003). First of all, we identified the Hα excess emitters in the $(m_{\text{F555W}} - m_{\text{F656N}})$ versus $(m_{\text{F555W}} - m_{\text{F814W}})$ color–color diagram shown in Fig. 1. The magnitudes were corrected for the extinction contribution of the Milky Way considering the values $A_{\text{F555W}} = 0.22$ mag and $E(m_{\text{F555W}} - m_{\text{F814W}})_{\text{MW}} = 0.1$ (Fitzpatrick & Savage 1984). To this aim, we selected from our catalog in F555W, F814W, and F656N bands all those stars whose photometric uncertainties, that is, $\delta_{\text{F555W}}$, $\delta_{\text{F814W}}$, and $\delta_{\text{F656N}}$, are less than 0.05 in each individual band. A total of 254 stars satisfied these conditions (gray filled dots in the color–color diagram in Fig.1), out of 9423 sources in the whole catalog. These are typically MS stars that do not present an appreciable Hα excess. With these stars, we define a reference sequence (dashed black line) with respect to which the excess Hα emission is computed. The dotted blue line of Fig. 1 represents the theoretical color relationship obtained using the Bessell et al. (1998) model atmospheres for MS stars with the chemical and physical parameters appropriate for the LMC (effective temperature $T_{\text{eff}}$ in the range of 3500–40000 K, surface gravity $\log g = 4.5$, and metallicity index $[M/H] = -0.5$, Colucci et al. 2012). The agreement between our reference sequence and the theoretical one is evident at $m_{\text{F555W}} - m_{\text{F814W}} < 1$. The discrepancy between the models and the data at $m_{\text{F555W}} - m_{\text{F814W}} > 1$ can be attributed to small number statistics and to the fact that the majority of these objects are red giants, with different physical characteristics from those assumed in the models.

To select the most probable PMS stars, after the exclusion of the 254 stars taken as reference, we first selected the targets with photometric uncertainties in each individual band as follows: $\delta_{\text{F555W}}$ and $\delta_{\text{F814W}} < 0.1$ mag, and $\delta_{\text{F656N}} < 0.3$ mag, for a total of 1309 objects. As highlighted by De Marchi et al. (2010), the contribution of the Hα line to the $m_{\text{F555}}$ magnitude is negligible, and

therefore we can define the magnitude of the excess emission as:

$$\Delta H \alpha = (m_{555} - m_{656})^{\text{obs}} - (m_{555} - m_{656})^{\text{ref}},$$  \hspace{1cm} (1)$$

where the superscripts "obs" and "ref" refer to the observation and reference sequence, respectively. We then considered the stars with $\Delta H \alpha$ exceeding at least three times the combined mean photometric uncertainties in the three bands $\delta_{3}$:

$$\delta_{3} = \sqrt{\frac{\delta_{555}^2 + \delta_{656}^2 + \delta_{814}^2}{3}}.$$  \hspace{1cm} (2)$$

A total of 187 stars satisfy these conditions; they are indicated with large red dots in Fig 1. This means that 187 stars have $(m_{555} - m_{656})$ colors exceeding that of the reference template at the given $(m_{555} - m_{814})$ color by more than three times the combined uncertainties on their $(m_{555} - m_{656})$ values. The large green dots in Fig 1 are the targets selected with $m_{555} < 20$ mag, which we exclude from our following analysis as we are interested primarily in low-mass PMS candidates. Our final sample of PMS candidates is therefore composed by 181 targets. As in these bands the reddening vector due to LH 91 runs almost parallel to the median of the reference sequence (De Marchi et al. 2010), the color–color diagram provides a robust identification of stars with H$\alpha$ excess even before correction for LH 91 reddening.

3.2. The color–magnitude diagram

We applied the correction for the extinction contribution of the Milky Way and LH 91 to the magnitudes in each band. For the Milky Way, we report the values in the previous section. We estimated the extinction for LH 91 from the value of $E(B-V) = 0.16 \pm 0.04$ color excess in the photometry of Gouliermis et al. (2002) and converted into $A_V$ assuming the average LMC reddening law $R_{555} = A_{555}/E(m_{555} - m_{814}) = 2.97$ calculated by De Marchi & Panagia (2014). As Gouliermis et al. (2002) found that the density of the ambient medium in LH 91 is similar to the value for LH 95, and as Da Rio et al. (2009) did not find a significant level of differential extinction while studying the upper MS stars of the latter, we also consider the differential reddening to be negligible in LH 91. We show the CMD $(m_{555} - m_{814})$ versus $(m_{555} - h_\alpha)$ in Fig. 2. The small black dots are the targets of the whole sample, namely 9423 stars. To estimate the age of the system, we fit the CMD with the isochrone models for ages 8 Myr and 1.5 Gyr, respectively, metallicity $Z=0.007$, and a distance modulus $(m-V)_0=18.55$.

![Fig. 1. Color–color diagram of the selected stars in the field of LH 91. All magnitudes are already corrected for the extinction contribution of our Galaxy. $A_{555}^{\text{MW}} = 0.22$ mag and $E(m_{555} - m_{814})^{\text{MW}} = 0.1$. The arrow shows the reddening vector of $(m_{555} - m_{814}) = 0.25$ and $E(m_{555} - m_{656})=0.13$ for the adopted LH 91 extinction law. The dashed line represents the median photospheric $(m_{555} - m_{814})$ color for the 254 stars with $\delta_{555}$, $\delta_{656}$, and $\delta_{814} < 0.05$ (gray filled dots). The dotted line shows the model atmospheres of Bessell et al. (1998) computed for the three WFC3/UVES filters. The PMS star candidates with H$\alpha$ emission excess at the 3σ level are represented with large red dots. The large green dots are the brightest PMS star candidates, with $m_{555} < 20$ mag. Error bars are also shown.](image1)

![Fig. 2. Color–magnitude diagram of the field of LH 91. All magnitudes are already corrected for the extinction contribution of our Galaxy and LH 91. The small black dots are the targets of the whole sample (9423 stars). Small gray-filled dots are the stars with photometric uncertainties $< 0.05$ mag in each band. The large red dots represent the PMS star candidates with H$\alpha$ excess emission at the 3σ level. Solid green and dashed light-blue lines show the theoretical isochrones from Bressan et al. (2012) for ages 8 Myr and 1.5 Gyr, respectively, metallicity $Z=0.007$, and a distance modulus $(m_V - M_V)_0=18.55$.](image2)
of the PMS candidates at different ages using the isochrone at 8 Myr as a discriminating factor. We divided the sample into stars older (blue dots) and younger (red squares) than 8 Myr (Fig. 3). Myr as a discriminating factor. We divided the sample into stars

3.3. From Hα color excess to Hα luminosity

To avoid contamination by stars with significant chromospheric activity, we also imposed constraints on \( EW_{\text{H} \alpha} \), selecting only stars with \( EW_{\text{H} \alpha} \geq 10 \, \AA \), because according to De Marchi et al. (2010) this is a reliable cutoff to separate accretors from those not accreting.

For details of the method used here to derive \( EW_{\text{H} \alpha} \) from the photometry, we refer to De Marchi et al. (2010, 2011, 2013). Here we recall that, as the width of the Hα line is narrow with respect to the width of the filter, the measure of \( EW_{\text{H} \alpha} \) is given by the difference between the observed Hα line magnitude and the level of the Hα continuum (\( \Delta H\alpha \)). If we assume that the stars used to define the reference sequence have no Hα absorption features, their \( (m_{555} - m_{656}) \) color represents the color of the pure continuum. Consequently, we calculated the \( EW_{\text{H} \alpha} \) from the following relation:

\[
EW_{\text{H} \alpha} = RECTW \times [1 - 10^{-0.4\Delta H\alpha}],
\]

where \( RECTW \) is the rectangular width of the F656N filter. The uncertainty on the \( EW_{\text{H} \alpha} \) measure is dominated by the uncertainty on the Hα magnitude.

Moreover, because of the width of the F656N filter, the small contribution due to the emission of the forbidden N II line at 6548 is included in \( \Delta H\alpha \). Therefore, following the prescriptions by De Marchi et al. (2010), we estimated corrections ranging from 0.2 to 1.4 Å, to be subtracted from the \( EW_{\text{H} \alpha} \) of our targets. Figure 3 shows the \( EW_{\text{H} \alpha} \) measured for the selected low-mass PMS candidates as a function of the de-reddened \( m_{555} - m_{656} \) color.

We performed a preliminary study of the \( EW_{\text{H} \alpha} \) distribution of the PMS candidates at different ages using the isochrone at 8 Myr as a discriminating factor. We divided the sample into stars older (blue dots) and younger (red squares) than 8 Myr (Fig. 3).

The values of \( EW_{\text{H} \alpha} \) for the sample range from \( \sim 3 \) Å to \( \sim 17 \) Å, with a median of \( \sim 9 \) Å that applies to both the whole sample and the two subgroups. After the selection on the \( EW_{\text{H} \alpha} \), a total of 75 objects satisfy the conservative condition (\( EW_{\text{H} \alpha} \geq 10 \, \AA \)).

The median value of the \( EW_{\text{H} \alpha} \) is about 12 Å, regardless of age, smaller than the values found in other star formation fields in the LMC, such as LH 95 (\( EW_{\text{H} \alpha} \sim 30 \, \AA \), Biazzo et al. 2019) and SN 1987A (\( EW_{\text{H} \alpha} \sim 20 \, \AA \), De Marchi et al. 2010). The difference could be due to the paucity and to stellar mass range of our sample. Moreover, the figure shows an almost clear separation in color between the two subgroups in LH 91 with the exception of the target with \( (m_{555} - m_{814}) = 0.4 \) and \( EW_{\text{H} \alpha} \sim 10 \, \AA \). As the coordinates of this target correspond to those of a massive star in the 2MASS catalog, it could be a Be star. A similar separation in color between the two subgroups of PMS stars was found in LH 95 (Biazzo et al. 2019).

The Hα emission line luminosity \( L_{\text{H} \alpha} \) can be determined from the absolute sensitivity of the instrumental setup, the photometric zero point (ZP), the distance of the stars, and from the magnitude in the Hα band:

\[
L_{\text{H} \alpha} = 4\pi d^2 10^{0.4(ZP-\text{mag})} \times \text{PHOTFLAM} \times RECTW.
\]

The values of the photometric properties of the instruments were taken from Ryon (2018), namely the inverse sensitivity PHOTFLAM= \( 1.714 \times 10^{-17} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Å}^{-1} \), and the zero point in the VEGAmag system for the Hα filter, ZP= 19.84 (Calamida et al. 2021). Assuming a distance of 51.4 ± 1.2 kpc (Panagia 1999) and considering the rectangular width of the F656N filter \( RECTW= 17.679 \, \AA \), we determined the Hα luminosity for the 75 targets, finding a median value of about \( 8.7 \times 10^{30} \, \text{erg s}^{-1} \) (0.2 \( \times 10^{-2} L_{\odot} \)).

This value is slightly lower than the one found by Biazzo et al. (2019) in the LH 95 association (\( \sim 1.2 \times 10^{31} \, \text{erg s}^{-1} \)), 0.3 \( \times 10^{-2} L_{\odot} \)). This is not surprising because Gouliermis et al. (2002) found that the mean Hα intensities of the HII region related to LH 95 (DEM L 252) is about two times higher than the corresponding intensity of the HII region associated with LH 91 (DEM L 251).

In addition, we can compared our result with the median Hα luminosity of other regions of the LMC, namely 30 Doradus Nebula and SN 1987A field; also in these cases our value is lower, the mean \( L_{\text{H} \alpha} \), estimated in these regions is \( \sim 4 \times 10^{31} \, \text{erg s}^{-1} \) (\( \sim 10^{-2} L_{\odot} \), De Marchi et al. (2010)) and \( \sim 1.5 \times 10^{32} \, \text{erg s}^{-1} \) (\( \sim 4 \times 10^{-2} L_{\odot} \), De Marchi et al. (2017)) respectively.

The uncertainty on \( L_{\text{H} \alpha} \) is dominated by the uncertainties on the Hα photometry, on the distance (\( \sim 5\% \)) and on instrumental setup (\( \sim 3\% \)) (see De Marchi et al. 2010). The total uncertainty on \( L_{\text{H} \alpha} \) is about 16%.

4. Physical parameters of the PMS candidates

4.1. Effective temperature and bolometric luminosity

We evaluated the effective temperature of the PMS candidates by comparing the theoretical models with the \( m_{555} - m_{656} \) color of our sample corrected for the reddening due to the Milky Way and LH 91, as explained in Sect. 3.2. To convert the color to \( T_{\text{eff}} \), we used the models of Bessell et al. (1998) for 3500 K < \( T_{\text{eff}} \) < 40000 K, log\( g \)=4.5, and metallicity index [M/H] =-0.5 dex. As the models of Bessell et al. (1998) are not available for temperatures lower than 3500 K, we used the \( T_{\text{eff}}(V - I_C) \) calibration by Pecaut & Mamajek (2013), with the assumption that the calibrated \( m_{555} \) and \( m_{814} \) magnitudes coincide with the \( V \) and \( I_C \) magnitudes (see Biazzo et al. 2019).

To obtain the luminosity of the stars \( L_\star \), we considered the magnitude \( m_{555} \) corrected for the interstellar extinction, a distance to LH 91 of 51.4 kpc (Panagia 1999), and a bolometric

---

**Fig. 3.** Hα equivalent width of the selected low-mass PMS candidates, as a function of the de-reddened \( (m_{555} - m_{656}) \) color. The red squares represent the values of the PMS stars younger than 8 Myr, the blue dots are the oldest PMS stars.
new_page

4.2. Mass and age

We derived the mass and age for each target by comparing the location of each star in the HR diagram (Fig. 5) with theoretical PMS evolutionary tracks. We adopted the PARSEC tracks for metallicity Z = 0.007 (Bressan et al. 2012) from 0.2 $M_\odot$ to 1.2 $M_\odot$ (dashed lines).

Solar magnitude of 4.74 mag (Pecaut & Mamajek 2013). The uncertainty on the effective temperature and stellar luminosity are dominated by the uncertainties on the magnitudes and distance. In Fig. 4, we show the location of the PMS candidates in the HR diagram, with the relative uncertainties, which in some cases are smaller than the symbol size. We highlight that the majority of the PMS candidates are close to the MS and we could only identify them thanks to the information on their Hα excess. We also plot in Figure 4 the theoretical isochrones for ages of 2, 4, 8, 16, 32, and 64 Myr for Z = 0.007 (Bressan et al. 2012). The red squares represent the PMS candidates younger than 8 Myr, while the blue dots the older ones.

From the HR diagram, it appears that LH 91 is characterized by a more or less continuous star formation, from a few million years to ~ 60 Myr, with a smaller number of PMS candidates for ages younger than 8 Myr.

The age distribution could suggest a separation between older and younger PMS stars, with a gap in the range between 5 and 10 Myr. The younger population shows a continuous distribution in mass, with no evident peak, but this is probably mostly due to the paucity of the subsample.

The age distribution could suggest a separation between older and younger PMS stars, with a gap in the range between 5 and 10 Myr. The younger population shows a continuous distribution in mass, with no evident peak, but this is probably mostly due to the paucity of the subsample.

5. Accretion properties

In the following subsections we describe how we determined the accretion properties of our sample of PMS candidates and we...
The luminosity of the H$\alpha$ line generated along the funnel flows of circumstellar gas during the magnetospheric accretion process can be used as a tracer to estimate the accretion luminosity. To determine the accretion luminosity of our sample of PMS candidates, we adopted the relationship obtained by De Marchi et al. (2010), who analyzed the data of a group of T Tauri stars in Taurus-Auriga compiled by Dahm (2008):

$$\log \frac{L_{\text{acc}}}{L_{\odot}} = \log \frac{L_{\text{H}\alpha}}{L_{\odot}} + (1.72 \pm 0.25). \quad (5)$$

The median of the accretion luminosity of our 75 PMS stars is 0.12 $L_{\odot}$. The uncertainty on $L_{\text{acc}}$ is dominated by the uncertainty on $L_{\text{H}\alpha}$, which is about 16%, related to the photometric error on the H$\alpha$ magnitude. There is also a systematic error to take into account due to the uncertainties on the ratio $L_{\text{acc}}/L_{\text{H}\alpha}$ (Dahm 2008; De Marchi et al. 2011), but as the relation is the same for all stars, this uncertainty does not interfere with the comparison between the targets.

In Fig. 6 we show the accretion luminosity versus $L_*$ of the PMS candidates, the blue dots and red squares representing the old and young ones, respectively. In each star formation region, $L_{\text{acc}}$ increases with stellar luminosity, but the range and dispersion of the data are quite different. For comparison, we show also the data of LH 95, with gray filled dots, SN 1987A with green empty diamonds, and 30 Dor with black empty dots. In LH 91 and LH 95, the dispersion in $L_{\text{acc}}$ seems to decrease with the increase of $L_*$. The accretion luminosity spans a range between 0.1 and 1 $L_*$, with the peak of the distribution at about 0.3 $L_*$ for LH91. In Section 3.3, we showed that the median $L_{\text{H}\alpha}$ in LH 91 is lower than that found in LH 95, and therefore it is not surprising that the values of the accretion luminosity in LH 91 are also slightly lower than those of the PMS objects in LH 95 ($\sim 0.17 L_{\odot}$). This result could be due to two main factors: in LH 95 the mass range of the sample is larger (0.2-1.8 $M_\odot$), and at the same mass the stars are younger. The samples of 30 Dor and SN 1987A are richer than LH 91 and LH 95, and the range of the accretion luminosity is larger, from 0.1 $L_*$ to values higher than 1.0 $L_*$. For a comparison, we focus on the range in stellar luminosity in common between the regions, namely -0.65 $L_*$ and 0.0 $L_*$.

In Fig. 7 we show the accretion luminosity versus $T_\text{eff}$ of our PMS objects in LH 91, respectively. The gray filled dots, green diamonds, and black empty dots are the PMS of LH 95 by Biazzo et al. (2019), SN 1987A by De Marchi et al. (2010), and 30 Dor by De Marchi et al. (2017), respectively. The dashed lines show the linear $L_{\text{acc}} - L_*$ relationship for different values of the coefficient, as indicated.

5.2. Mass accretion rate versus stellar age

Finally, we derived the mass accretion rate $\dot{M}_{\text{acc}}$ of our PMS candidates from the free-fall equation (Koenigl 1991; Calvet & Gullbring 1998):

$$L_{\text{acc}} = \frac{GM_\star \dot{M}_{\text{acc}}}{R_\star} \left(1 - \frac{R_\star}{R_{\text{in}}} \right), \quad (6)$$

where $G$ is the gravitational constant, $M_\star$ and $R_\star$ are the mass and radius of the PMS candidates, and $R_{\text{in}}$ is the inner radius of
the accretion disk. \( R_{\text{in}} \) depends on how exactly the accretion disk is coupled with the magnetic field of the star, and so its value is quite uncertain. We adopt \( R_{\text{in}} = 5 R_{\odot} \), following Gullbring et al. (1998). The median value of the mass accretion rate of our sample is \( \sim 4.8 \times 10^{-9} M_{\odot} \text{yr}^{-1} \), with higher values for the younger population (\( \sim 1.2 \times 10^{-8} M_{\odot} \text{yr}^{-1} \)), and lower values for the older candidates (\( \sim 4.7 \times 10^{-9} M_{\odot} \text{yr}^{-1} \)). The values we find are slightly lower than those found by Biazzo et al. (2019) for LH 95, as shown in Fig. 9, where the median rate is about \( 7.5 \times 10^{-9} M_{\odot} \text{yr}^{-1} \).

The mass accretion rate in LH 91 is also lower than the median value measured in the field of SN 1987A (\( 2.6 \times 10^{-8} M_{\odot} \text{yr}^{-1} \), as found by Romaniello et al. 2004, and \( 2.9 \times 10^{-8} M_{\odot} \text{yr}^{-1} \) as measured by De Marchi et al. 2010) and in 30 Dor by (\( 8 \times 10^{-8} M_{\odot} \text{yr}^{-1} \); De Marchi et al. 2017). The uncertainty on \( M_{\text{acc}} \) is dominated by the uncertainty on \( L_{\text{H\alpha}} \), which is of about 16%, but we have to consider also the contribution of \( R_{\text{in}} \) (7%, including a 5% systematic uncertainty on the distance modulus), stellar mass (\( \sim 7\% \)), the intrinsic uncertainties due to the evolutionary tracks (2%-6%, for more details see the Appendix A of Biazzo et al. 2019), and knowledge of the relation \( L_{\text{acc}} - L_{\text{H\alpha}} \), which in this case is not very accurate (a factor of \( \sim 2 \); De Marchi et al. 2010). Finally, the contribution of other sources of systematic error —such as physical processes different from accretion (e.g., chromospheric activity or ionization of nearby massive stars) or nebular continuum—that could affect the determination of \( M_{\text{acc}} \) are considered to be negligible (De Marchi et al. 2010). In summary, the combined statistical uncertainty on \( M_{\text{acc}} \) is of about 20%.

A snapshot of the mass accretion rate as a function of the age is shown in Fig. 9. We divided the sample in two subsamples with the stellar mass larger (yellow filled squares) and smaller (empty black triangles) than the median stellar mass (\( \sim 0.8 M_{\odot} \)). The gray filled dots are the PMS candidate in LH 95 (Biazzo et al. 2019). As expected, the accretion appears to decrease with time, in line with the predicted evolution of viscous disks (Hartmann et al. 2016), but there is a large spread in mass accretion rate at a given age. We performed a linear fit to the two subsamples, and find a similar slope: \(-0.31 \pm 0.07 \) for the high masses and \(-0.39 \pm 0.04 \) for the low masses. These values are in agreement within the error with those evaluated in other MCs regions (De Marchi et al. 2011, 2013, 2017; Biazzo et al. 2019). This plot also shows that the mean mass accretion rate of the PMS stars in LH 91 is slightly lower than in LH 95, because our sample is composed mainly of older stars (more so than 30 Myr), close to the MS when the accretion process is less powerful.

5.3. Mass accretion rate versus stellar mass

Figure 10 shows the mass accretion rate as a function of the stellar mass of our PMS candidates. Younger PMS candidates are represented by red squares, while the older PMS candidates are marked with blue dots. The gray filled dots represent the PMS candidates in LH 95 (Biazzo et al. 2019). From Figs. 9 and 10 it is evident that the mass accretion rate is typically higher for the younger and more massive stars. Only two low-mass stars (with masses of about 0.3 \( M_{\odot} \) and 0.4 \( M_{\odot} \)) have a high mass accretion rate (\( 2.2 \times 10^{-8} M_{\odot} \text{yr}^{-1} \) and \( 1.4 \times 10^{-8} M_{\odot} \text{yr}^{-1} \) respectively). Figure 10 reveals a large spread in \( M_{\text{acc}} \) values for a given stellar mass. This is hardly surprising considering the large spread of ages (see also Rigliaco et al. (2011)). Moreover, the older sample of PMS candidates in LH 91 reaches lower values of mass accretion rate when compared to the stars at similar masses in LH 95. Again, it is interesting to note how the stars of any given mass appear to be younger in LH 95 than in LH 91. This could simply be the result of different evolutionary stages between stars in LH 91 and LH 95, with the former sample being more evolved than the latter. This could also explain the smaller number of accretors and the lower values of the mass accretion rate in LH 91 compared to LH 95. This difference might in turn be caused by other physical differences in the star formation environment, for example the gas density of the regions. It would seem natural that an environment with lower
Fig. 10. Distribution of $M_{\text{acc}}$ as a function of $M_\star$. The symbols are as in Fig. 7.

gas density would result in less massive circumstellar disks, and therefore a more modest mass accretion rate. To verify this effect, we compare the median mass accretion rate in LH 91 with that of the three star-forming regions at similar metallicity in the LMC, namely LH 95, SN 1987A, and 30 Dor, for which a study of accretion properties was performed. Considering targets with the same mass range ($0.4-1.0M_\odot$) and younger than 8 Myr, we obtained a mean $M_{\text{acc}}$ value of $1.1 \times 10^{-8}M_\odot$/yr for LH 91, $4.4 \times 10^{-8}M_\odot$/yr for LH 95, $3.7 \times 10^{-7}M_\odot$/yr for SN 1987A, and $5.9 \times 10^{-8}M_\odot$/yr for 30 Dor. We also estimated the mean dust density of the aforementioned four regions taking into account the mass surface density map by Utomo et al. (2019). Considering regions with a radius of 1.5 arcmin, we found values of $0.11 \pm 0.01M_\odot$/pc$^2$ for LH 91, $0.16 \pm 0.01M_\odot$/pc$^2$ for LH 95, and similar value for SN 1987A, and $0.65 \pm 0.09M_\odot$/pc$^2$ for 30 Dor. Even though this kind of analysis is only qualitative, we find some tentative indication that regions with higher dust densities also have higher mass accretion rates (and possibly higher gas density), with the exception of SN 1987A. A much more detailed analysis would be necessary to address this issue in more detail, which goes beyond the scope of this work.

5.4. Spatial distribution of the PMS candidates

The left panel of Figure 11 shows a color-composite image from WFC3 observations in the F555W (red), F814W (blue), and F656N (green) filters of LH 91. The right panel in the same figure shows the spatial distribution of the PMS stars in our sample projected onto the sky. As in figure 5, the sizes of the dots and squares are proportionate to the ranges of the mass accretion rate. Different colors represent different ages: older than 8 Myr (blue dots) and younger than 8 Myr (red squares). The crosses are massive stars selected from the 2MASS catalog (Cutri et al. 2003) with $J-H < 0.8$ and $J < 15$ mag (see also Biazzo et al. 2019), while the triangles are Be stars found by Gouliermis et al. (2002) (see their Table 1). To align the orientation of the two figures, the left image is rotated 30 degrees. With the aim of better understanding the correspondence between the fields, we indicate some bright stars with the letters A to D. Regions with a lack of stars in the right figure correspond to those rich in gas in the left figure, shown in green. The dust associated to the gas could be obscuring the stars behind it. The PMS objects appear to be distributed more or less uniformly over the region, and are not clustered around the massive stars, unlike the younger population of LH 95 (Biazzo et al. 2019). This result is in agreement with the conclusions of Gouliermis et al. (2002), who found only a weak match between the HII region of LH 91 and the two Be stars located to the southwest side of the region. Therefore, it appears that in LH 91 there is no obvious region of higher star-formation intensity, at least currently.

6. Conclusions

We presented a multiwavelength analysis of the stellar populations in LH 91, a star-forming region in the LMC, observed with the WFC3 on board the HST. We applied a photometric detection method to identify PMS candidates still actively accreting matter from their circumstellar disks. The method combines HST broad-band F555W and F814W photometry with narrow-band F656N imaging in order to identify stars with H{$\alpha$} excess emission and to subsequently measure their accretion luminosity $L_{\text{acc}}$ and equivalent width $EW_{\text{H} \alpha}$, and to derive their mass accretion rate $M_{\text{acc}}$. The main results of our analysis can be summarized as follows:

1. From the photometric catalog of 9423 well-detected stars, we identified about 180 low-mass PMS candidates on the basis of their excess H{$\alpha$} emission, that is, with their $(m_{555} - m_{656})$ color exceeding that of the reference template at the same $(m_{555} - m_{654})$ color by more than three times the combined uncertainties on their $(m_{555} - m_{656})$ values.
2. We measured the $EW_{\text{H} \alpha}$ of the PMS stars, finding values in the range of $\sim 3$ Å - 17 Å, with a median of 9 Å. We selected stars with $EW_{\text{H} \alpha} \geq 10$ Å, which are typical values of actively accreting PMS stars. A total of 75 objects satisfy this condition.
3. We estimated the stellar effective temperature and luminosity thanks to the Bessell et al. (1998) relations for $3500 \leq T_{\text{eff}} \leq 40000$ K, and the Pecaut & Mamajek (2013) calibrations for $T_{\text{eff}} < 3500$ K.
4. We obtained the mass and age of the PMS candidates by comparing the location of each star in the HR diagram with theoretical PMS evolutionary tracks (Bressan et al. 2012). The range of the stellar masses in our sample is between $0.2M_\odot$ and $\sim 1.0M_\odot$ with a median of $0.8M_\odot$. The age of the stars is distributed between a few million years and as much as $\sim 60$ Myr with an apparent gap between 5 Myr and 10 Myr. For this reason we divided our sample into two populations, which we call younger ($t \leq 8$ Myr with median age $\sim 3.5$ Myr) and older PMS candidates ($t > 8$ Myr with median age $\sim 35$ Myr).
5. We measured the H{$\alpha$} luminosity of the PMS candidates and consequently their accretion luminosity. We find a median value of $\sim 0.12L_\odot$. The accretion luminosity increases with $L_\star$, while the dispersion in $L_{\text{acc}}$ seems to decreases with $L_\star$. We also find that the accretion luminosity spans the range $0.1-1L_\star$, with a peak in the distribution at about $0.3L_\star$.
6. Through the accretion luminosity and other physical parameters, we determined the mass accretion rate of PMS stars, finding a median value of $\sim 4.8 \times 10^{-9}M_\odot$/yr$^{-1}$, with higher values for the younger population ($\sim 1.2 \times 10^{-8}M_\odot$/yr$^{-1}$), and lower values for the older candidates ($\sim 4.7 \times 10^{-9}M_\odot$/yr$^{-1}$).
7. We studied the relation between the mass accretion rate and both age and stellar mass. As expected, the mass accretion rate appears to decrease with time and to increase with stellar mass.

8. We compared our results with other star formation regions in the Large Magellanic Cloud, in particular with LH 95, which is the closest region to LH 91 for which accretion properties of PMS candidates have been derived. LH 91 is a star-forming region that is less rich in PMS stars than LH 95, with lower stellar masses (0.2-1.0 $M_\odot$) and similar range in age (few Myr vs 0.2-1.8 $M_\odot$) but different dust density (0.2-1.0 $M_\odot$) and younger than 8 Myr. From a qualitative analysis, we find that the mass accretion rate increases with dust density of the environment in which the stars are formed.

9. We explored the possibility that the density of the environment (which we probe using dust emission) could affect the mass accretion rate. We compared the median mass accretion rate of star-forming regions with similar metallicity but different dust density, namely LH 91, LH 95, SN 1987A, and 30 Dor. We considered targets in the same mass range (0.4-1.1 $M_\odot$) and younger than 8 Myr. From a qualitative analysis, we find that the mass accretion rate increases with dust density of the environment in which the stars are formed.

10. Finally, we find the spatial distribution of the PMS stars to be rather uniform, without any evidence of clumps around more massive stars.

The advent of the James Webb Space Telescope will allow us to put strong constraints on accretion phenomena of members in star-forming regions with different stellar properties (such as metallicity, age, and distance). In particular, the spectroscopic observations would give us information on the density and ionization state of the material undergoing accretion as well as on its kinematics, thereby providing a clearer picture of the accretion process itself in different environmental conditions.

Acknowledgements. We are very thankful to the anonymous referee for precious comments and suggestions that have helped us to improve this paper. RC is grateful to ESA for the support during the data analysis useful for the preparation of this paper. This work was based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). Some of the data presented in this paper were obtained from the Mikulski Archive for Space Telescopes (MAST). STScI is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This research made use of the SIMBAD database, operated at the CDS (Strasbourg, France) and data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. This research has made also use of the SVO Filter Profile Service supported from the Spanish MINECO through grant AYA2014-55216.

References

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, VizieR Online Data Catalog, II/246

Fig. 11. Left panel: Color-composite image of LH 91 from WFC3 observations in the F555W, F814W, and F656N filters. The image is rotated 30 degrees to align the two figures. Right panel: Distribution of the PMS stars. Symbols are the same as in Fig. 5. The crosses represent the massive stars from the 2MASS catalog, and the triangles are Be stars from Table 1 of Gouliermis et al. (2002). North is up and east to the left.
Romaniello, M. 1998, PhD thesis, -
Ryon, J. E. 2018, Advanced Camera for Surveys Instrument Handbook for Cycle 26 v. 17.0