Three generations of stars: a possible case of triggered star formation

M. B. Areal, A. Buccino, S. Paron, C. Fariña and M. E. Ortega

1 CONICET-Universidad de Buenos Aires. Instituto de Astronomía y Física del Espacio CC 67, Suc. 28, 1428 Buenos Aires, Argentina
2 Departamento de Física. FCEyN-Universidad de Buenos Aires, Buenos Aires, Argentina.
3 Isaac Newton Group of Telescopes, E38700, La Palma, Spain.
4 Instituto de Astrofísica de Canarias (IAC) and Universidad de La Laguna, Dpto. Astrofísica, Spain.

Accepted XXX. Received YYY; in original form ZZZ.

ABSTRACT

Evidence for triggered star formation linking three generations of stars is difficult to assemble, as it requires convincingly associating evolved massive stars with HII regions that, in turn, would need to present signs of active star formation. We present observational evidence for triggered star formation relating three generations of stars in the neighbourhood of the star LS II +26 8. We carried out new spectroscopic observations of LS II +26 8, revealing that it is a B0 III-type star. We note that LS II +26 8 is located exactly at the geometric centre of a semi-shell-like HII region complex. The most conspicuous component of this complex is the HII region Sh2-90, which is probably triggering a new generation of stars. The distances to LSII +26 8 and to Sh2-90 are in agreement (between 2.6 and 3 kpc). Analysis of the interstellar medium on a larger spatial scale shows that HII region complex lies on the northwestern border of an extended H2 shell. The radius of this molecular shell is about 13 pc, which is in agreement with what an O9V star (the probable initial spectral type of LS II +26 8 as inferred from evolutive tracks) can generate through its winds in the molecular environment. In conclusion, the spatial and temporal correspondences derived in our analysis enable us to propose a probable triggered star formation scenario initiated by the evolved massive star LS II +26 8 during its main sequence stage, followed by stars exciting the HII region complex formed in the molecular shell, and culminating in the birth of YSOs around Sh2-90.

Key words: stars: massive – stars: formation – (ISM): HII regions

1 INTRODUCTION

Triggered star formation linking two generations of stars has been studied, mainly at the interfaces between HII regions and molecular clouds. It is usually observed that the older generation, i.e. the exciting stars of an HII region, triggers the formation of a new generation of stars at the HII region’s periphery (e.g. Duronea et al. 2017; Deharveng et al. 2015; Zavagno et al. 2010, 2007). The exciting stars of the HII regions of course also have a formation history, but it is very difficult to find any evidence for it because of the complexity of the interstellar medium (ISM) and the time scales involved. Thus, evidence for triggered star formation linking three generations of stars is difficult to assemble, as it requires convincingly associating evolved massive stars with HII regions that, in turn, would need to present signs of active star formation. Indeed, observational evidence is scant and in general involves superstructures (e.g. supershells) in the ISM. For instance, Oey et al. (2005) argue that they identified the first example of three-generation, hierarchical triggered star formation in the W3/W4 Galactic star-forming complex. Parker et al. (1992), Walborn & Parker (1992), and Barbá et al. (2003) have also suggested a case of possible sequential star formation among three generations of OB associations towards the N11B nebula in the Large Magellanic Cloud.

In the following sections we present observational evidence pointing to a likely Galactic case of triggered star formation among three generations of stars.

2 PRESENTATION OF THE CASE

The star LS II +26 8 (α2000=19h50m12.7s, δ2000=+26°58′35″) was catalogued, based on photometric criteria, as a possible OB-type star (Stock et al. 1960). Bailer-Jones et al. (2018) obtained the parallax of LS II +26 8 and estimated a distance of between 2.8 and 3.5 kpc. Inspection of the ISM surrounding the star reveals an interesting configuration. Figure 1 is a three-colour image showing the 8 and 4.5 μm emission extracted from the GLIMPSE/Spitzer survey in green and blue, respectively, and 24 μm obtained from...
the MIPS/Spitzer survey in red. It can be seen that LS II +26 8 is located exactly at the geometric centre of a semi-shell-like H\textsc{ii} region complex (with a radius of about 15\arcmin). Are the LS II +26 8 star and the H\textsc{ii} region complex related?

The semi-shell-like H\textsc{ii} region complex consists of a set of H\textsc{ii} regions belonging to Sh2-90 (Sharpless 1959) and the H\textsc{ii} region HRDS G063.137+00.252 (Bania et al. 2012), marked as G63 in Fig. 1. These are related to a molecular cloud that extends from 15.5 to 28.5 km s\(^{-1}\) with a mean velocity of about 20.8 km s\(^{-1}\) (Lafon et al. 1983; Samal et al. 2014). The latter authors, using the galactic rotation curve of Brand & Blitz (1993) to convert the mean velocity of the molecular cloud to distance and other indirect distance estimation methods, suggest that the distance to Sh2-90 lies in the range 2.1–2.5 kpc. This distance is somewhat close to the lower value of the distance to LS II +26 8 determined from parallax. In addition, if the galactic rotation curve of Fich et al. (1989) is used, the mean velocity of the molecular gas has an associated distance of about 3 kpc, in close agreement with the distance estimated for LS II +26 8. Moreover, using the revised kinematic distance estimate based on the method described in Reid et al. (2009) (Section 4)\(^1\) together with the Galactic parameters from the A5 model of Reid et al. (2014), we obtain a distance of 2.5 ± 1.0 kpc for Sh2-90. In conclusion, we suggest that it is very likely that the star LS II +26 8 and the H\textsc{ii} region complex are located close enough to be physically related.

Sh2-90, which has an age < 6.5 × 10\(^6\) yr (Samal et al. 2014), is probably excited by a loose cluster of massive stars, of which the most massive member is an O8–O9V star. According to the authors, Sh2-90 is very probably triggering star formation. More than 100 young stellar object (YSO) candidates with masses in the range 0.2–3 M\(_\odot\) were found in its neighbourhood.

Given that this is a promising region to relate a possible evolved massive star with H\textsc{ii} regions that are triggering star formation, and that we were probably registering a case of triggered star formation among three generations of stars, we performed spectroscopic optical observations to get an accurate determination of the spectral type of LS II +26 8 and investigate the surrounding ISM along the circumference shown in Fig. 1.

3 OBSERVATIONS

The visible spectrum of the star LS II +26 8 was obtained with the Intermediate Dispersion Spectrograph (IDS) mounted on the 2.5 m Isaac Newton Telescope at Roque de los Muchachos Observatory on 2019 October 22. We employed the R900V grating, which allows us to obtain the spectrum in the 3800–5200 Å wavelength range with a mean dispersion of 0.69 Å per pixel.

Two consecutive images were obtained to filter out the cosmic rays in the combined spectrum. The images were bias-corrected and the spectrum was optimally extracted and wavelength calibrated using standard IRAF\(^2\) routines. The wavelength calibration was derived from the CuAr+CuNe arc-lamp spectra obtained at target position. The rms values of the wavelength calibration were less than 0.5 Å. The resulting spectrum has a high S/N (~200) at 4500 Å. The spectrum was normalized using standard IRAF tasks.

---

1. bessel.vlbi-astrometry.org/revised_kd_2014
2. Image Reduction and Analysis Facility (IRAF) is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
be identified as a MIPSGAL bubble (MB) (e.g. Mizuno et al. 2010; Flagey et al. 2014). As those authors indicate, most MBs are thought to be associated with stars, some of them massive, in the late stages of evolution. In those cases, the just-mentioned bubble morphology can be produced as a consequence of the star’s evolution: as its atmosphere expands and cools, the ejected gas condenses into dust grains within a circumstellar shell that emits at mid-IR wavelengths. The morphology of the 24 μm emission observed in LS II +26 8 is quite similar to that observed towards MB 3701 generated by MN95, a B0 I star (Flagey et al. 2014), and towards MB 3955 (Nowak et al. 2014), which is generated by the star CD-61 3738, a likely OBe-type star (Stephenson & Sanduleak 1971).

According to Hohle et al. (2010), the bolometric luminosity of a B0 III type star can be $(1.60–2.06) \times 10^4 L_\odot$. Using this value and the magnitude $m_V = 12.14$ (Zacharias et al. 2012) in the typical equation:

$$\log(L_{bol}/L_\odot) = 0.4(5 \log(d/10 \text{ pc}) + 4.8 – BC – m_V + A_V)$$

(1)

with the bolometric correction $BC = -2.8$ for a B0 star and a visual extinction $A_V = 2.91$ (from $R_V = A_V/E(B-V)$, with $E(B-V) = 0.97$, estimated using the $V$ and $B$ magnitudes of Zacharias et al. 2012, the intrinsic colour from Wegner 1994, and $R_V = 3.0$), we derive a distance to the star in a range between 2.68 and 3.04 kpc. This calculation of the distance is totally independent of the distance estimates discussed in Sect. 2. Thus, we can confirm

Table 1. Relevant absorption lines identified in Fig. 2 with their equivalent widths.

| Sp. line | $\lambda$ | EW | Sp. line | $\lambda$ | EW |
|---------|-----------|----|---------|-----------|----|
| He i    | 3820      | 0.8336 | Si iii  | 4552      | 0.3213 |
|         | 3927      | 0.5039 |         | 4568      | 0.2588 |
|         | 4009      | 0.3752 |         | 4575      | 0.1723 |
|         | 4026      | 0.8601 | Si iv   | 4089      | 0.2816 |
|         | 4121      | 0.6157 | N ii    | 3995      | 0.1841 |
|         | 4144      | 0.4746 | N iii   | 4116      | 0.1955 |
|         | 4169      | 0.0571 |         | 4144      | 0.4746 |
|         | 4388      | 0.5187 | O ii    | 4089      | 0.2816 |
|         | 4471      | 0.4998 |         | 4542      | 0.2816 |
|         | 4713      | 0.2951 |         | 4730      | 0.2537 |
| He ii   | 4924      | 0.6457 |         | 4076      | 0.2834 |
|         | 4942      | 0.0351 |         | 4350      | 0.3118 |
|         | 4542      | 0.0245 |         | 4416      | 0.3807 |
|         | 4686      | 0.1644 |         | 4676      | 0.1968 |
| Mg ii   | 4481      | 0.1849 |         |           |     |

Figure 2. Spectrum of the LS II +26 8 obtained with the IDS at the Isaac Newton Telescope.

Figure 3. MIPS/Spitzer emission at 24 μm (red) and the J broad-band emission (blue) from 2MASS towards the star LS II +26 8.
that LS II +26 8 and the H\textsc{ii} region complex are indeed located at the same distance.

4.2 The ISM around LS II +26 8 on a large spatial scale

With the aim of finding evidence supporting the hypothesis that the massive evolved star LS II +26 8 has swept up molecular gas that probably gave rise to the stars exciting the H\textsc{ii} region complex shown in Fig. 1, we investigate the ISM surrounding the star on a larger spatial scale. Unfortunately, at these Galactic latitudes/longitudes there is no molecular line survey covering the whole region. However, from the mid- and far-IR bands obtained from the Herschel-Hi-GAL survey (Molinari et al. 2010) it is possible to derive an H\textsubscript{2} column density map that indicates the distribution of molecular gas around LS II +26 8.

We obtained an H\textsubscript{2} column density map generated from the PPMAP procedure carried out on the Hi-GAL maps in the wavelength range 70–500 $\mu$m (see Marsh et al. 2017). Figure 4 shows the distribution of the H\textsubscript{2} column density. It can be seen that the star LS II +26 8 is located exactly at the geometrical centre of a large H\textsubscript{2} open shell in whose northwestern/western border lies the above-described H\textsc{ii} region complex. By inspecting the catalogues of massive/luminous stars in the VizieR and SIMBAD Astronomical Database we find that LS II +26 8 is the only massive star that lies within the molecular shell. Some weaker N(H\textsubscript{2}) features are observed within the circumference drawn by the shell, which could be due to material on the back and/or front borders of the probably expanding shell. This scenario supports the hypothesis that an extinct H\textsc{ii} region excited by LS II +26 8 and/or its stellar winds could have generated the observed shell in which the massive stars responsible of Sh2-90 and G63 were born.

4.3 Association between LS II +26 8 and the molecular shell

It is known that a massive star loses a large amount of mass in the form of stellar wind. The winds expand into the surrounding medium and collide with the gas in the ISM, generating a low density bubble that expands over time (van Marle et al. 2015; McKee et al. 1984).

The location of LS II +26 8 exactly at the geometrical centre of a molecular semi-shell, strongly suggests a causal connection between both, so we wondered whether this star was able to create such a molecular structure in the ISM. Massive stars interact with the interstellar medium throughout their entire evolution. Hence, we have to take into account the possibility that, before reaching the B0 III stage, LS II +26 8 had evolved from a hotter main sequence star of an earlier spectral type. Thus, using the evolutionary tracks for massive stars of Ekström et al. (2012) and the luminosity value of about $1.83 \times 10^4$ L\odot for a B0 III type star mentioned above, LS II +26 8 lies somewhere between the 12–15 M\odot evolutionary tracks, which correspond to an O9V.

Using the equation presented in Chevalier (1999) for a wind-blown bubble radius ($R_B$):

$$R_B = 15.8 \left( \frac{M}{10^{-8} M_\odot \text{yr}^{-1}} \right)^{1/3} \left( \frac{v_w}{10^3 \text{ km s}^{-1}} \right)^{2/3} \left( \frac{\tau_{\text{max}}}{10^1 \text{ yr}} \right)^{1/3} \left( \frac{p/k}{10^5 \text{ K cm}^{-3}} \right)^{-1/3} \left( \frac{\tau}{10^{-3} \text{ yr}} \right)^{1/3} \left( \frac{M}{M_\odot} \right)^{-1/3} \left( \frac{v}{300 \text{ km s}^{-1}} \right)$$

with a time in the main sequence of $\tau_{\text{max}} \sim 10^7$ yr, a mass loss rate $M \sim 6 \times 10^{-8} M_\odot \text{yr}^{-1}$, and a terminal wind velocity $v_w \sim 1300$ km s\textsuperscript{-1} (values corresponding to an O9V star, see Kobulnicky et al. 2019, 2018; Chen et al. 2013; Chevalier 1999), and assuming the typical interstellar medium pressure of $p/k = 10^5$ K cm\textsuperscript{-3}, we obtain $R_B$ about 13 pc.

Assuming a distance about 2.8 kpc for the region, the radius of the molecular semi-shell is $\sim 12.2$ pc, which is in agreement with the radius of the wind-blown bubble estimated above, thus supporting the hypothesis that LS II +26 8 is responsible of the molecular semi-shell presented in Fig. 4. Additionally, considering that LS II +26 8 is a B0 III star, its age should be $\geq 10^7$ yr, whereas Sh2-90 has an age $< 6.5 \times 10^6$ yr (Samal et al. 2014). A comparison of these times gives support to the proposed scenario of probable triggered star formation.

5 SUMMARY AND CONCLUSION

Evidence for triggered star formation linking several generations of stars is difficult to assemble. Based on a detailed study of the star LS II +26 8 and the surrounding ISM, we present a plausible case for triggered star formation that links three generations of stars. We focus on LS II +26 8 because it was catalogued as a possible OB-type star, and a semi-shell-like H\textsc{ii} region complex, which in turn presents signs of triggered star formation, that seems to be related to it. Our main results are as follows:

(a) From our spectroscopic optical observations carried out with the Isaac Newton Telescope at Roque de Los Muchachos Observatory, we classified LS II +26 8 as a B0 III, i.e. an evolved massive star.

(b) Analysing the mid-IR emission towards LS II +26 8, we note that the star is embedded in a bubble that emits at 24 $\mu$m, thus supporting the case that LS II +26 8 is a massive star that has left the main sequence.

(c) Using a range of bolometric luminosity corresponding to a
B0 III type star and the optical magnitudes measured for this star, we determine that LS II +26 8 is located at a distance of about 2.8 kpc. Additionally, by following evolutionary tracks for massive stars we note that during its life on the main sequence the spectral type of the star should have been O9.

(d) We observe that LS II +26 8 is located exactly at the geometric centre of a semi-shell-like H\textsc{ii} region complex (15′ in radius). It is known that the H\textsc{ii} region Sh2-90, which belongs to this complex, has more than 100 YSO candidates in its vicinity. The estimated distances to LS II +26 8 and to Sh2-90 are in agreement.

(e) Analysing the distribution of the H$_2$ column density obtained from Hi-GAL maps in the wavelength range 70–500 µm, we observe an extended shell also of 15′ in radius on whose northwestern border lies the H\textsc{ii} region complex. LS II +26 8 is located exactly at its geometric centre and is the only catalogued massive star within the shell.

(f) Assuming a distance about 2.8 kpc to the region, the radius of the molecular shell is ~ 13 pc, which is in agreement with what an O9V star can generate through its winds in the molecular environment.

Based on the above points, we conclude that we have presented strong evidence pointing to a probable triggered star-forming scenario. The action of LS II +26 8 could have triggered the formation of the exciting stars of the H\textsc{ii} region complex at the shell, which in turn, is very probably triggering a new generation of stars.

ACKNOWLEDGEMENTS

We thank the anonymous referee for her/his very helpful comments and suggestions. We are especially grateful to Terry Mahoney for the language revision of the manuscript. M.B.A. is a doctoral fellow of CONICET, Argentina. A.B., S.P. and M.O. are members of the Carrera del Investigador Científico of CONICET, Argentina. The INT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias.

REFERENCES

Bailer-Jones C. A. L., Rybizki J., Fouesneau M., Mantelet G., Andrae R., 2018, AJ, 156, 58
Bania T. M., Anderson L. D., Balser D. S., 2012, ApJ, 759, 96
Barbá R. H., Rubio M., Roth M. R., García J., 2003, AJ, 125, 1940
Brand J., Blitz L., 1993, A&A, 275, 67
Chen Y., Zhou P., Chu Y.-H., 2013, ApJ, 769, L16
Chevalier R. A., 1999, ApJ, 511, 798
Deharveng L., et al., 2015, A&A, 582, A1
Duronea N. U., Cappa C. E., Bronfman L., Borissova J., Gromadzki M., Kuhn M. A., 2017, A&A, 606, A8
Ekström S., et al., 2012, A&A, 537, A146
Fich M., Blitz L., Stark A. A., 1989, ApJ, 342, 272
Flagay N., Noriega-Crespo A., Petric A., Geballe T. R., 2014, AJ, 148, 34
Hohle M. M., Neuhäuser R., Schutz B. F., 2010, Astronomische Nachrichten, 331, 349
Kobulnicky H. A., Cheadle W. T., Povich M. S., 2018, ApJ, 856, 74
Kobulnicky H. A., Cheadle W. T., Povich M. S., 2019, AJ, 158, 73
Lafon G., Deharveng L., Baudry A., de La Noë J., 1983, A&A, 124, 1
Liu Z., Cui W., Liu C., Huang Y., Zhao G., Zhang B., 2019, ApJS, 241, 32
Marsh K. A., et al., 2017, MNRAS, 471, 2730
McKee C. F., van Buren D., Lazareff B., 1984, ApJ, 278, L115
Mizuno D. R., et al., 2010, AJ, 139, 1542
Molinari S., et al., 2010, PASP, 122, 314

This paper has been typeset from a TEX/LATEX file prepared by the author.