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Planetary Nebulae and the Ionization of the Interstellar Medium in Galaxies

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We discuss the role of planetary nebulae and their progeny in galaxy context in terms of ionization of the galaxy interstellar medium. This regards ionized gas outside the disk of spiral galaxies, the diffuse ionized medium in spiral galaxies, and the weak line emission of elliptical galaxies.

Keywords: planetary nebulae, galaxies, ionization, interstellar medium, stellar population

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1 INTRODUCTION

Until recently it was considered that the only stellar ionization sources in galaxies are massive stars. However, low- and intermediate-mass stars (LIMS) are far more numerous (Salpeter, 1955; Kroupa, 2001) and many (if not or most) pass through a stage where they produce ionizing photons evidenced by the spectacular planetary nebula (PN) phenomenon which produces the beautiful images of celestial objects known to all sky lovers. The planetary nebula stage is actually very short on an astronomical timescale–just about a few thousand years (Jacob et al., 2013)—but LIMS by far outnumber the massive stars in galaxies. Besides, after the proper PN stage, when the nebulae have dispersed in the general interstellar medium, their central stars stay hot enough to produce ionizing photons that can travel in the diffuse gas of the galaxies (Marigo et al., 2004).

In the early nineties, Bruzual and Charlot (1993) assembled an evolutionary stellar population synthesis code which was, among many other things, able to quantify the number of ionizing photons emitted by an aging starburst as a function of time, including the photons produced by evolved LIMS. Then Binette et al. (1994) computed the emission-line spectrum that would be produced in the gas surrounding these 'post-AGB' stars and compared the results to the–very scarce at that time–data on the weak emission lines observed in elliptical galaxies. They also noted that the ionizing energy distribution of the population of these 'post-AGB' stars (better called HOLMES for 'hot low-mass evolved stars'[1]) was much harder than that of massive stars. This implies that elliptical galaxies with weak emission lines should show emission-line ratios similar to those of LINERs and lie above the H II region sequence in the [O III]/Hβ versus [N II]/Hα diagram, called the BPT diagram (Baldwin et al., 1981). This led Stasińska et al. (2008) to propose that, in the BPT diagram constructed for galaxies from the Sloan Digital Sky Survey (SDSS; York et al., 2000; Adelman-McCarthy et al., 2007), many of the galaxies situated in the right wing and so far considered to be composed of galaxies with a (weakly) active galactic nucleus (AGN) are actually ionized by the old stellar populations

[1]Since 2010, we prefer to use the term HOLMES rather than 'post-AGB' to avoid confusion with 'proto planetary nebulae' which are also commonly referenced as 'post-AGB' in the PN community. In addition, the term HOLMES does not exclude stars which may provide ionizing photons without having reached the tip of the AGB.

found in these galaxies. They nicknamed them 'retired galaxies' (as opposed to 'active' with reference to star formation), and suggested that nuclear activity related to a central black hole is not as common as thought before.

In the next section we summarize the paper by Stasińska (2012) which gave an overview of what was known on the topic at that time.

Many processes other than HOLMES have been invoked to explain the line emission properties of the diffuse ionized gas (DIG) observed in galaxies of all types such as shocks (Collins and Rand, 2001), turbulence (Slavin et al., 1993; Binette et al., 2009), magnetic reconnection (Lazarian et al., 2020), dust scattering (Barnes et al., 2015), ionizing photons escaping from H II regions in the case of late-type galaxies. HOLMES, however, cannot be ignored as they are natural components in any evolved stellar population.

In **Section 3** we briefly review the important advances made since 2012 in the observation of the DIG in galaxies. These are mainly due to the increasing use of integral field units in observational astronomy. New models have been computed for the evolution of LIMS that take into account the important progress achieved in stellar physics these last decades. In **Section 4** we present these models and compute their effects on evolving stellar populations. We present and discuss a few pending issues in **Section 5** and conclude in the last Section.

2 WHAT WE KNEW UNTIL 2012

2.1 Elliptical and LINER-Like Galaxies

In 2008, the number of galaxies with spectra in the 3900–9500 Å range amounted to nearly one million galaxies, thanks to the SDSS (York et al., 2000; Abazajian et al., 2009). Analysis of these spectra with inverse spectral synthesis tools (such as STARLIGHT by Cid Fernandes et al., 2005) allowed one to decompose the complex stellar populations of these galaxies into simple stellar populations (SSP) of various ages and metallicities. In such a way one could not only determine the galaxies star formation and chemical histories but also dig out weak emission lines from stellar emission. Such a procedure revealed that a large fraction of elliptical galaxies do present emission lines, at a low level. Applying STARLIGHT to the SDSS galaxies, Stasińska et al. (2008) found that galaxies with LINER-like spectra[2], have stopped forming stars and contain old stellar populations whose HOLMES can easily produce the emission-line ratios observed in these galaxies. The observed Hα luminosities can be accounted by the HOLMES in about one third of the LINER-like galaxies present in the BPT diagram. In order to distinguish galaxies ionized by HOLMES from galaxies ionized by a weak AGN (LINERs), Cid Fernandes et al. (2011) proposed the WHAN diagram, where the Hα equivalent width, $W(\mathrm{H}\alpha)$, is plotted versus [N II]/Hα. Using this diagram, five spectral classes can be identified in the entire population of galaxies:

- Pure star forming galaxies: log [N II]/Hα < -0.4 and $W(\mathrm{H}\alpha) > 3$ Å
- Strong AGNs (i.e., Seyferts): log [N II]/Hα > -0.4 and $W(\mathrm{H}\alpha) > 6$ Å
- Weak AGNs: log [N II]/Hα > -0.4 and $3 < W(\mathrm{H}\alpha) < 6$ Å
- Retired galaxies (i.e., fake AGNs): $W(\mathrm{H}\alpha) < 3$ Å
- Passive galaxies (actually, line-less galaxies): $W(\mathrm{H}\alpha)$ and W ([N II]) < 0.5 Å

Integral field spectroscopy of LINER-like galaxies has confirmed that in many of them the ionization is indeed due to HOLMES and not to a weak AGN (Annibali et al., 2010; Sarzi et al., 2010).

2.2 The DIG in Spiral Galaxies

In spiral galaxies, the main ionizing source is due to the massive OB stars located in the thin disk and Hα images show many bright H II regions linked to these stars. However, between these H II regions one also detects diffuse ionized gas. By studying 109 H I selected galaxies in the SINGS survey, Oey et al. (2007) came to the conclusion that diffuse Hα emission is present in galaxies of all types representing about 60% of the total Hα emission, irrespective of the galaxy Hubble type or total star formation rate. DIG was also detected in edge-on spirals (Dettmar, 1990; Hoopes et al., 1996) even at several kiloparsecs from the galactic plane. While leakage of photons from massive stars out of the H II regions may contribute to ionize the DIG, it has been shown that this cannot explain the increase of [N II]/Hα, [S II]/Hα [O II]/Hβ and [O III]/Hβ with galactic height, which require a hardening of the ionizing photons. HOLMES, on the other hand, have a radiation field roughly similar to that of a 10^5 K star and are thus an obvious candidate for the ionization and heating of the DIG, since they are expected to be plentiful in the old stellar populations of the thick discs and lower haloes of spiral galaxies. Using the edge-on spiral galaxy NGC 891 as a test case, Flores-Fajardo et al. (2011) showed that the estimated content of HOLMES in this galaxy well explains the observed emission-line characteristics of its extraplanar DIG.

3 RECENT OBSERVATIONS OF THE DIG

3.1 DIG With IFS Observations

The recent explosion of studies using integral field spectroscopy (IFS) has provided a wealth of new observational data allowing one to study the DIG in galaxies of all types and orientations at different spatial resolutions, and to better quantify the effect of HOLMES. For example analyzing a sample of 32 early-type galaxies (ETG) from the CALIFA survey (Sánchez et al., 2016),

[2]LINER was a term coined by Heckman (1980) to designate 'low ionization nuclear emission regions' in galaxies. In the BPT diagram, objects with LINER-like spectra lie above the H II region sequence, and to the lower left of the Seyfert branch, see e.g., Kauffmann et al. (2003).

Gomes et al. (2016) found that in half of them the radial distribution of diagnostic line ratios is of the LINER-type in both their nuclear and extranuclear zones and that the distribution of $W(\mathrm{H}\alpha)$ is compatible with the HOLMES hypothesis (the other half of the galaxies being devoid of gas in the central zones). Using data from the entire CALIFA survey, Lacerda et al. (2018) showed that $W(\mathrm{H}\alpha)$ is a better discriminant of the DIG than the commonly used surface-brighness in Hα which gives flawed indications in the bulges of late-type galaxies. They also showed that the DIG contribution to the total Hα luminosity varies in a systematic way along the Hubble sequence, increasing from late-to early-types.

Gomes et al. (2016) found that about half of their ETGs are dominated by rotation, and many of those show decoupling between gas and stellar kinematics. Other studies have looked at the kinematics of the extraplanar DIG in edge-on galaxies, e.g., Levy et al. (2019), who have investigated a sample of 25 edge-on galaxies observed by CALIFA and in CO with CARMA, and Rautio et al. (2022), whose sample consists of 5 edge-on galaxies observed with MUSE and deep narrowband Hα imaging. Both works showed that, for many of their galaxies, the Hα rotation velocity decreases above the midplane. They also measured the ionized gas velocity lag as a function of the galactocentric radius; Levy et al. (2019) found the extraplanar DIG to be linked to star formation activity in the disk, while Rautio et al. (2022) concluded that their results point to a complex external and/or internal origin for the ionized gas.

3.2 Other Options Than HOLMES

Among additional sources to ionize the DIG, Woods and Gilfanov (2014) suggested accreting, steadily nuclear-burning white dwarfs with effective temperatures of several 10^5 K that produce super-soft X-ray sources. To test this hypothesis, Johansson et al. (2014, 2016) stacked the spectra of 11 500 gas-rich retired galaxies from the SDSS in several age ranges, allowing them to measure the intensities of the weak He II λ4686 and [O I] λ6300 lines. These lines provide additional diagnostics to the usual lines used in the BPT diagram, allowing one to estimate the relative populations of hot ionizing sources–accreting white dwarfs or HOLMES–that can produce the observed intensities in these weak lines. Johansson et al. (2014, 2016) concluded that in the presence of the expected population of HOLMES, accreting white dwarfs provide a negligible contribution to the ionization of the DIG.

3.3 Effect of DIG on Abundances From Emission Lines in Galaxies

The chemical composition of late-type galaxies is obtained from the lines emitted by their H II regions. A review of the methods for abundance determinations in H II regions can be found in Stasińska (2009). The method considered as the most accurate is the so-called 'temperature-based' or 'direct' method, in which the electron temperature is derived directly from a temperature-sensitive observed line ratio such as [O III] λ4363/5,007, followed by the computation of ionic abundances from the observed emission line intensities. In most cases, however, it is not possible to apply this technique because the lines allowing the measurement of the temperature are not observed. One must use statistical methods, the so-called 'strong line methods' which rely on empirical relations between intensity ratios of strong lines and the oxygen abundances in H II regions. These relations are based either on the observations of H II regions where the weak auroral lines have been detected, or on photoionization models for H II regions. Thus those calibrations do not take into account the contribution from the DIG to the emission-line spectra in star-forming galaxies. Since collisional-to-recombination line ratios such as [N II] λ6584/Hα and [O II] λ3727/Hβ are usually enhanced in the DIG, strong line methods may yield biased oxygen abundances.

Zhang et al. (2017), using a sample of 365 face-on star-forming galaxies from Mapping Nearby Galaxies at APO (MaNGA, Bundy et al., 2015), have characterized DIG regions as those having small values of Hα surface brightness. They concluded that strong emission line calibrations based on [N II] λ6584/Hα, [O III] λ5007/[N II] λ6584, ([O II] λ3727+[O III] λ5007)/Hβ and a combination of [N II] λ6584/[S II] λ6716, λ6731 and [N II] λ6584/Hα are unreliable, due to their broad distribution of O/H residuals as a function of Hα surface brightness. They considered that a calibration based on [N II] λ6584/[O II] λ3727 is relatively safe. They also compared emission line ratios with a set of photoionization models, and concluded that the radiation escape from OB stars alone is unable to model those line ratios and the addition of ionization by HOLMES is needed. The mixing of leaking radiation from H II regions and HOLMES to model the DIG emission is further explored by Belfiore et al. (2022) at higher resolution for a sample of 19 nearby galaxies from the PHANGS–MUSE survey (Emsellem et al., 2022). They found that models with leakage only are able to account for most of the Hα emission, but a harder ionizing spectra from HOLMES is required to explain the behaviour of the line ratios such as [O III] λ5007/Hβ, [N II] λ6584/Hα, [S II] λ6716, λ6731/Hα and [O I] λ6300/Hα.

Vale Asari et al. (2019) have proposed corrections for emission line luminosities due to the emission from the DIG based on a sample of 1,409 face-on star-forming galaxies from MaNGA. They have identified the DIG as contaminating spaxels of low $W_{\mathrm{H}\alpha}$, following Lacerda et al. (2018). Those corrections were then applied to a sample of $>$90 000 SF galaxies from the SDSS. Removing the DIG contribution has a non-negligible impact on the shape of the stellar mass-oxygen abundance-star formation relation, which has been used as a key empirical input for chemical evolution models (e.g., Lilly et al., 2013). This study was limited by the low spatial resolution of MaNGA and would need to be updated with higher resolution data to see the real (probably larger) impact of the DIG on chemical abundance measurements.

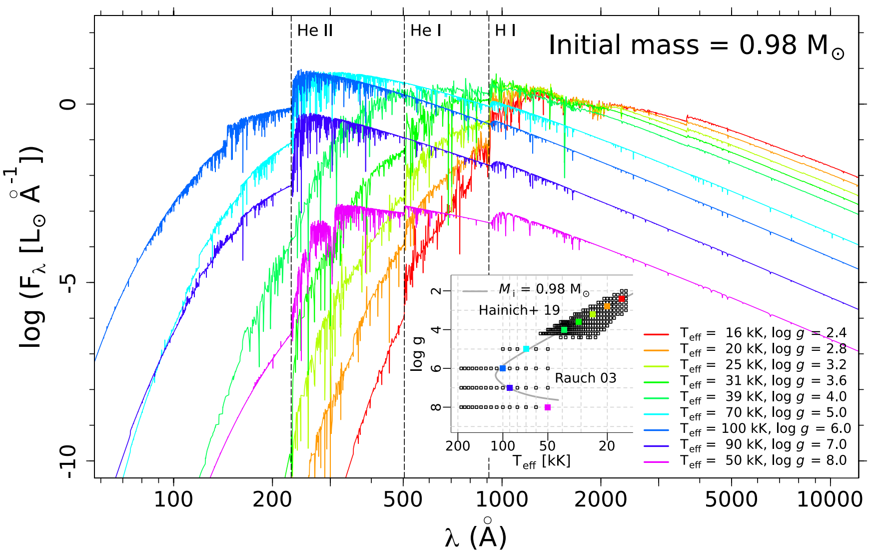

FIGURE 1 | Evolution of the spectrum of a star with initial mass of 0.98 $M_{\odot}$ and solar metalicity. The inner panel shows the HOLMES evolutionary sequence by Miller Bertolami (2016) (*grey line*) and the parameters (effective temperature and surface gravity) of stars in the Rauch (2003) and Hainich et al. (2019) libraries of stellar spectra (*open squares*). The coloured squares indicate the parameters of the stars for which spectra are shown in the main panel. The star takes 3.4 Myr to evolve from the first (*red*) to the last (*purple*) phase shown in this Figure.

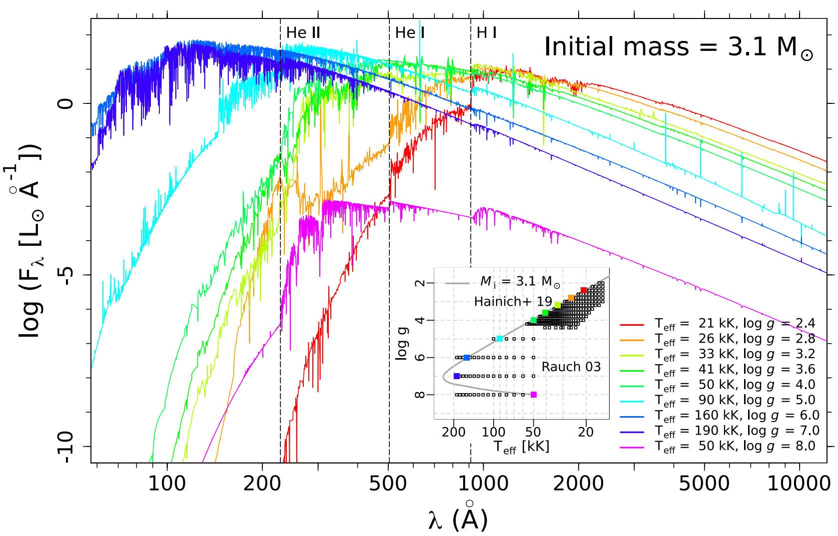

FIGURE 2 | The same as **Figure 1**, but for a star with initial mass of 3.1 $M_{\odot}$. The time elapsed between the first (*red*) and the last (*purple*) phase is 1.6 Myr.

4 NEW MODELS FOR HOLMES AND STELLAR POPULATION MODELS INCLUDING THEM

4.1 Stellar evolution

All the discussions regarding the effect of HOLMES on the ionization interstellar gas in galaxies rely on stellar evolution models of the 80–90s (Schoenberner, 1981; Vassiliadis and Wood, 1993; Bloecker, 1995), even for the most recent papers (with the exception of Byler et al., 2019). However, a significant update of evolutionary models for LIMS up to the white dwarf stage has been performed by Kitsikis and Weiss (2007), Weiss and Ferguson (2009), and, most importantly by Miller Bertolami (2016). While the Miller Bertolami's models are now widely used for planetary nebulae studies, they have not been incorporated so far in stellar population studies. In the next section, we explain how we incorporated them and how the resulting stellar population models differ from the previous ones.

The models by Miller Bertolami include the improvements that have been carried out in stellar physics since the mid 90s:

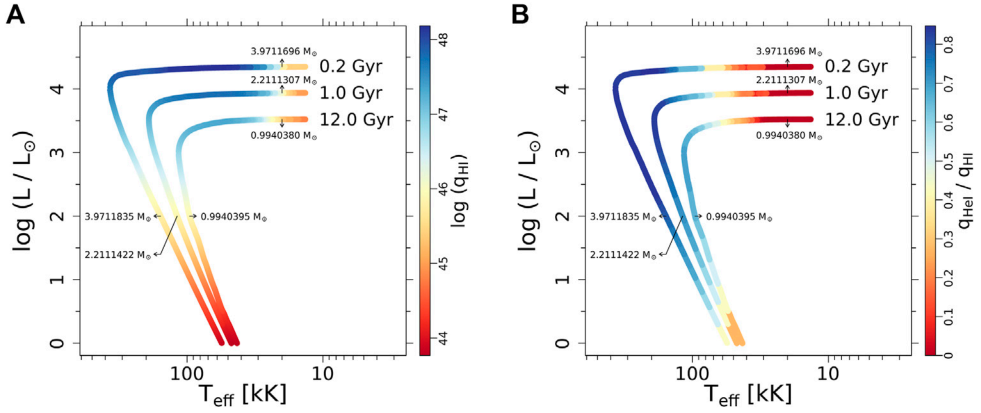

FIGURE 3 | Isochrones in the luminosity *vs*. effective temperature plane for stellar populations with 0.2, 1.0 and 12 Gyr and solar metallicity. The points along the isochrones are colour-coded according to their $\log q_{\mathrm{H\,I}}$ **(A)** and $q_{\mathrm{He\,I}}/q_{\mathrm{H\,I}}$ ratio **(B)**, where $q_{\mathrm{H\,I}}$ and $q_{\mathrm{He\,I}}$ are the H I and He I ionizing photon rates in units of s^{-1}. The masses of stars in two different points along each isochrone are indicated; the mass difference between these points is on the order of 10^{-5} and 10^{-6} $M_{\odot}$ for the populations with 0.2 and 12 Gyr, respectively.

modern opacities, nuclear reaction rates, equations of state, conductive opacities, neutrino emission rates, and additional mixing processes. As a result, the post-AGB models are at least 3–10 times faster than the models of similar mass in the older grids, and 0.1–0.3 dex more luminous than the older ones at similar remnant masses. As noted by Miller Bertolami, the shorter timescales are in agreement with the results obtained for a restricted mass range by Kitsikis (2008) and Weiss and Ferguson (2009) using a completely independent code but also with updated physics.

The contribution of HOLMES to the ionizing flux is illustrated in **Figures 1**, **2**, where we show the evolution of the spectra of HOLMES with solar metallicity and initial masses of 0.98 $M_{\odot}$ (**Figure 1**) and 3.1 $M_{\odot}$ (**Figure 2**). The spectra shown in these figures were taken from the stellar libraries by Hainich et al. (2019) and Rauch (2003), as indicated in the inner panels, and rescaled to have the total luminosity given by the Miller Bertolami (2016) models. The hardening of the ionizing photons during the hottest HOLMES phases can be clearly seen.

Given the big changes in the predicted evolution of HOLMES, it is natural to ask how they affect the computed output of ionizing photons produced by aging stellar populations.

4.2 Simple Stellar Populations With the New Stellar Tracks

To incorporate the new evolutionary sequences by Miller Bertolami (2016) into stellar population models, we interpolated the tracks to generate the isochrones and created the model spectra of single-age, single metallicity HOLMES

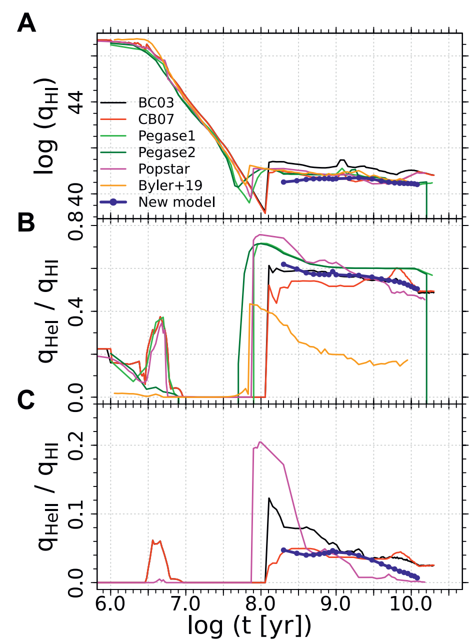

FIGURE 4 | Evolution of the H I ionizing photon rates in units of $s^{-1}\,M_{\odot}^{-1}$ **(A)**, the ratio between the He I and H I ionizing photon rates **(B)**, and between the He II and H I ionizing photon rates **(C)**. We show the predictions from solar-metallicity models by Bruzual and Charlot (2003, B03, *black lines*); an updated version of BC03 (CB07, *red*); two sets of models by Fioc and Rocca-Volmerange (1997, Pegase1 and Pegase2 in *light* and *dark green*, respectively); models by Mollá et al. (2009, Popstar, *magenta*); and a more recent model by Byler et al. (2019, Byler+19, *orange*). Our stellar population models computed with the new post-AGB evolutionary sequences by Miller Bertolami (2016) are shown in blue.

populations. To interpolate the evolutionary models, we calculated the curvature of the evolutionary sequences, applied the dynamic time warping technique–implemented in the R package `dtw` (Giorgino, 2009)–to find the optimal alignment between the tracks, and performed the interpolation. We used stellar spectra from the Hainich et al. (2019) and Rauch (2003) spectral libraries and adopted a Chabrier initial mass function (Chabrier, 2003) with lower and upper mass limits of 0.08 and 100 $M_{\odot}$, respectively.

In the left panel of **Figure 3**, we show the H I ionizing photon rates, $q_{H\ I}$, of individual stars along isochrones of HOLMES populations with different ages (0.2, 1.0, and 12 Gyr). HOLMES hotter than 25 ,000 K and brighter than 2000 $L_{\odot}$ have ionizing photon fluxes $q_{H\ I} > 10^{47}\ s^{-1}$ and are present in populations of all ages. The hardness of the ionizing photons of individual stars, quantified by the ratio between the He I and H I ionizing photon rates ($q_{He\ I}/q_{H\ I}$), is presented in the right panel of **Figure 3**. HOLMES with effective temperatures greater than ~70 ,000 K have $q_{He\ I}/q_{H\ I} > 0.5$ and are also present in populations of all ages. On the other hand, it is clear from these figures that more massive HOLMES in younger stellar populations can reach higher values of $q_{H\ I}$ and $q_{He\ I}/q_{H\ I}$ than low-mass HOLMES. The maximum H I ionizing photon rates of HOLMES in a 0.2-Gyr population is ~ 8 times higher than that in a 12-Gyr stellar population. In addition, in a 12-Gyr population, there are no stars with $q_{He\ I}/q_{H\ I} > 0.7$, while for HOLMES in a 0.2-Gyr population $q_{He\ I}/q_{H\ I}$ can be as high as 0.85.

The figures discussed above give us an idea of how HOLMES with different initial masses contribute to the ionizing flux of stellar populations with different ages. However, we need to take into account that HOLMES contributing to the ionizing flux in younger stellar populations are less numerous and pass through the HOLMES phase faster than the less-massive HOLMES found in older stellar systems. As a result, the flux of H I ionizing photons remains approximately constant with time after 100 Myr, as shown in the top panel of **Figure 4**. In this figure, we also show the evolution of the He I and He II ionizing photon rates relative to the flux of H I ionizing photons, and compare our predictions with those of other models from the literature. After 100 Myr, $q_{He\ I}/q_{H\ I}$ slightly decreases with time, going from $q_{He\ I}/q_{H\ I} = 0.62$ to 0.50 between 0.2 and 12 Gyr. A similar decrease is also observed for the previous models. On the other hand, the flux He II ionizing photon decreases by a factor of almost 9 from 0.2 to 12 Gyr, making $q_{He\ II}/q_{H\ I}$ decrease from approximately 0.05 to 0.007.

Finally, we compare our results with predictions from the recent model by Byler et al. (2019), who computed self-consistent stellar population models using evolutionary tracks from MIST (Choi et al., 2016; Dotter, 2016). In the MIST models, the HOLMES phase is faster and brighter than in the old generation of models, in agreement with the models calculated by Miller Bertolami (2016). The Byler et al. predictions for the evolution of H I ionizing photon rates and q_{HeI}/q_{HI} ratios are shown in **Figure 4**. While there their predictions for the $q_{H\ I}$ evolution is similar to that of other models, it can be seen that their models lead to lower He I ionizing photo rates when compared to other models, including ours. The source of this difference will be investigated in a future study.

5 PENDING PROBLEMS

5.1 Origin of the Gas Ionized by HOLMES

Since all old stellar populations contain HOLMES in similar proportions, why is it that about half of the elliptical galaxies in the SDSS do not show emission lines at all (Stasińska et al., 2015)?

It should be noted that the mass of gas needed to produce the emission line luminosities in 'liny'[3] retired galaxies is smaller by orders of magnitudes than the total mass lost by winds in AGB and post-AGB stars in these galaxies: Following Herpich et al. (2018) the mass of gas needed to produce the Hα luminosity in liny retired galaxies is given by

$$M_g = 13 \times L(\mathrm{H}\alpha)\big/n_e, \tag{1}$$

where both L (Hα) and M_g are in solar units, and n_e is the average electron density in cm^{-3}. For a density of 100 cm^{-3} as found by Johansson et al. (2016) from stacked spectra of retired galaxies, this gives $M_g \sim 10^5\ M_{\odot}$. This corresponds to the mass of gas injected into the ISM by stellar mass loss during only a few million years (Belfiore et al., 2017) in these retired galaxies.

But is it really the gas coming from stellar winds that produces the line emission in liny retired galaxies? Herpich et al. (2018) found that in the liny galaxies, the [N II]/[O II] sequence as a function of galaxy mass prolongates exactly the [N II]/[O II] sequence of star-forming galaxies, indicating that the emitting gas is not enriched in nitrogen in a way similar to what is seen in PNe and thus must have an external origin.

An additional argument for an external origin of the emitting gas in liny retired galaxies is that gas arising from stellar winds is expected to have the same kinematic signatures as that of the parent stars, which is at odds with the observations (Belfiore et al., 2017).

Herpich et al. (2018) compared in detail the properties of lineless and liny retired galaxies. Starting from a clean sample of SDSS ellipticals with good signal-to-noise spectra, they built a sample of 59,662 liny retired galaxies and 96,844 lineless retired galaxies (defined by W(Hα) smaller that 0.5 Å). To meaningfully compare the galaxy properties in the two samples, they pair-matched the two samples by total stellar mass, half-light radius in the r band and redshift (the latter to avoid aperture effects due to the fixed diameter of the SDSS fiber). No differences were seen in the total output of ionizing photons expected from HOLMES from a stellar population analysis. The difference in mean stellar ages is at the limit of significance. But there is a significant difference in the dust

[3]The term 'liny' was introduced by Herpich et al. (2018) to distinguish retired galaxies showing emission lines from those where no emission lines could be detected after a careful subtraction of the stellar continuum using inverse spectral synthesis tools such as STARLIGHT.

attenuation estimated from the stellar continuum, being higher for liny galaxies. Mid-infrared data from the WISE explorer (Wright et al., 2010) in the *W*2 and *W*3 bands indicate that the luminosity in the *W*3 band is greater in liny galaxies, pointing to the presence of polycyclic aromatic hydrocarbon (PAH) 11.2 and 12.7 micron features, which are greatly enhanced in the presence of the hard UV field able to excite the PAH grains (Draine and Li, 2007). Also data from the GALEX survey (Morrissey et al., 2007) show a slightly higher flux in the near-UV for liny galaxies. All this seems to indicate some low-level recent star formation. Since, as mentioned above, the gas producing the emission lines is not enriched in nitrogen, this new generation of stars must have been made of gas having an external origin. It probably comes from accretion from the haloes of the galaxies, or from residual streams of metal-rich gas coming from a merger in the recent past. Thus, the ionization source and the origin of the gas producing the emission lines are disconnected!

One still unanswered question is what happens to the gas ejected by the stellar winds. *A priori* one would expect it to be present in all the retired galaxies. Calculations show that gas from stellar-mass loss (Parriott and Bregman, 2008) and PNe (Bregman and Parriott, 2009) in early-type galaxies is quickly heated to very high temperatures and it is not clear whether the amount of remaining warm gas is sufficient to explain the observed Hα luminosities.

5.2 The Effect of Binaries

The works mentioned so far consider only single stars. However it is known that about 60% of LIMS evolve in binary systems (e.g., Kamath, 2019). Evolution in binary systems can be affected by mass transfer due Roche-lobe overflow which results in a change of the mass distribution and lifetimes of the stars (Han et al., 2010). It can even prevent certain stars from reaching states predicted in single-star evolution. For example some stars may never become red giants due to early removal of their hydrogen envelopes (Stanway and Eldridge, 2018; Xiao et al., 2018). On the other hand, the population of certain stellar types can be greatly increased, such as that of hot subdwarfs which are produced mostly in binary interactions and naturally explain the so-called UV upturn observed in elliptical galaxies (Han et al., 2007).

But what about HOLMES? Because binary evolution can result in mass transfer between stars or even in the production of merged stars (see **Figure 1** in Han, 2003) the mass distribution of PN progenitors will be different from the one that would be found in a population of single stars.

Binary population synthesis codes have flourished these past 20 years (see references in Han et al., 2020), mostly to investigate exotic objects but also to investigate the global effects that stellar populations with binaries may have on the properties of galaxies (e.g., Stanway and Eldridge, 2020). However, to our knowledge, the problem of ionizing photons produced by HOLMES in binary scenarios has not been addressed so far.

Is it expected to be important? Estimates of the fraction of binaries among central stars of planetary nebulae could give some clue. Unfortunately such estimates are not accurate and vary among authors from about 20 to 70% with huge error bars (see Boffin and Jones, 2019). It is likely that, unless the population of PNe with binary central stars is dominant, their integrated effect on the Lyman continuum radiation produced by HOLMES in galaxies will not greatly differ from the predictions from single star population syntheses, but this point requires further investigation.

6 CONCLUSION

As this whole book demonstrates[4], PNe, in addition to being interesting objects in their own right, play a more general role in Astronomy. For example, PNe and their progenies (and progenitors) have a collective effect on certain properties of galaxies. The role of LIMS on the chemical evolution of galaxies has been known for many decades. The effect of HOLMES in the production of emission lines in early-type galaxies has been demonstrated only recently and has been the subject of this short paper, where we presented the present-day knowledge on this topic. It led to the concept of 'retired galaxies', i.e., galaxies that stopped forming stars and are ionized by their old stellar populations. This concept has gained more and more supporters and has changed the astronomers' view on the demography of AGNs in the local Universe (Stasińska et al., 2015), since many of the galaxies formerly thought to contain a weakly active nucleus are actually simply ionized by HOLMES.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

GS, MT, and NVA contributed to conception and design of the study. MT performed the computations presented in **Section 4**. GS wrote the first draft of the manuscript. MT and NVA wrote sections of the manuscript. All authors contributed to manuscript revision, and have read and approved the submitted version.

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[4]See also the proceedings of the conference 'Planetary Nebulae as Astronomical Tools'(Szczerba et al., 2005).

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