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EVOLUTION OF H II REGIONS

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ABSTRACT. In this paper the influence of the evolution (aging) on general properties of the H II regions is analyzed. The problem of the parametricity, the line ratios generally used as metallicity indicators, and the H II regions as distance calibrators are particularly discussed. Existing determinations of age in the LMC, SMC, and BCG are reviewed. An analysis of radio data on VH+ and VHe+ to determine ages for H II regions of the Milky Way is presented. Finally, it is also discussed the new idea on the link between H II region evolution and nuclear activity in galaxies.

Key words: GALAXIES-NUCLEI — NEBULAE-H II REGIONS

I. INTRODUCTION

One of the most important questions in modern astronomy, related to HII regions, is that of stellar formation (S. von Hoerner 1975). We believe that stars are formed by the gravitational collapse of molecular clouds. The classical idea that in this process the less massive stars take more time to collapse (Hayashi 1966; Roberts 1960) has some counter-arguments (Iben and Talbot 1966), and is also questioned by observational evidences (Melnick 1985; Lequeux et al. 1981, LMDK) at least for a range including masses up to 2 M☉.

As we know, the largest part of stars are born explosively, in compact groups (LMDK), where less massive stars are more frequent. The upper mass limit (Mu) seems to be related to the mass of the cloud from which stars were formed (Larson 1982), and/or to the metallicity (Panagia 1980). As a consequence of the birth of the most massive stars in stellar association appears the HII region, whose external appearance is intrinsically bounded to the evolution of these stars, although many characteristics of the emission spectra are determined by the metallicity of the cloud. Taking in mind this peculiarity, we will discuss the way by which some features give information about the properties of the ionizing association such as initial mass function (IMF), upper mass limit (Mu), and state of evolution (age) of the ionizing association.

We will also discuss the influence of the ageing on the lines ratios normally used to measure metallicity of the emitting gas; the variation of the HII region diameter with age and the possible correction that could be made when using HII regions as distance indicators; determination of age from relative volume of He to H for HII of the Milky Way; and the activity in Seyfert 2 and Liners as resulting from the evolution of special types of HII regions (Terlevich and Melnick 1985).

II. HII REGION AGE INDICATORS

The first models suggested to detect the state of evolution of the ionizing association in HII regions, developed in order to explore IUE data, were those of LMDK, who modeled the evolution of the UV flux produced by an evolving ionizing association. Simultaneously, we analyzed $W_{H\beta}$, the equivalent width of the Hβ emission line, as a function of time, also modeling ionizing association (Dottori 1981). The underlying concept in our work is very similar to that of Zanstra's temperature (Zanstra 1931; Harman and Seaton, 1966). The intensity of the Hβ line is indicative of the total number of Lyman photons, produced by the rapidly evolving massive stars, while the neighboring continuum shows the contribution of the less massive stars with longer mean life in the Main Sequence. Other authors have also modeled WHβ (Tarrab, 1985; Melnick, Terlevich and Eggleton 1985 ; Copetti, Pastoriza and Dottori 1986, CPD2).

2.1 The Evolution of UV Flux

The behavior of the UV continuum as a function of time, obtained by LMDK for different IMF, can be seen in figure 1. This type of relation seems more suitable for more evolved systems than HII regions and could possibly be a link between the scale of age of HII regions and open clusters, or blue clusters as in the LMC. The conclusion of LMDK is that the star formation occurs in burst of short duration, the IMF is flatter than x = 2, it is possible to determine the age of the burst, and the total mass of stars formed in the burst.

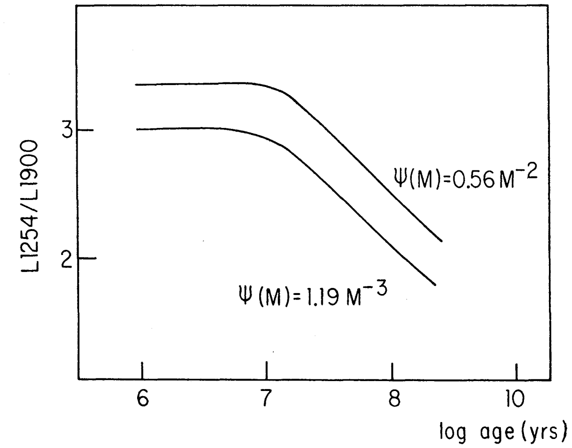


Fig. 1. Evolution of the UV flux for two different IMF (data from LMDK).

2.2 WHβ,[OIII]/Hβ and R = VHe+/VH+ as Age Indicators

The three quantities, WHβ,[OIII]/Hβ, and R = VHe+/VH+, were fully modeled by Copetti (1983, see also CPD1) taking into account models of star evolution with and without mass loss, different IMF and Mu, and covering a wide range of metallicities. Figures 2a, b, and c show the typical behavior of the parameters as a function of time. The full grid of CPD2 models show that:

WHβ is not influenced by Te and Ne. Mu is important in the initial phase of the evolution until 4E6 years. It is strongly sensitive to IMF,varying by 1/7 when $1 \leq x \leq 3$. $\dot{M}$ plays a secondary role. This last result is substantially changed for special cases of mass loss for stars embedded in metal rich gas (Terlevich and Melnick 1985), which will be discussed later.

R = VHe+/VH+ is practically unaltered during the first million years and then it falls quickly. It is not sensitive to Mu larger than 60 M⊙ and to the initial mass function. R gives the ratio of He to H ionizing photons, and consequently it measures a property of the hottest stars.

The ratio [OIII]/Hβ, first proposed as a metallicity indicator (Jensen, Strom and Strom 1976) is strongly affected by the evolution. It is sensitive to the density, insensitive to the IMF, and saturated by the radiation produced by stars more massive than 40 $M_\odot$.

Our models show that the metallicity does not determine univocally the state of an HII region as claimed by Mc Call et al. (1985). The dispersion in their diagram WHβ vs [OII]+[OIII]/Hβ could be a consequence of the evolution on the observed sample of HII regions.

Tarrab (1983) suggests the complementary use of different age indicators. The WHβ, for example, can be affected by the existence of an underlying population, as seems to be the case of some extragalactic HII regions (Dottori 1983).

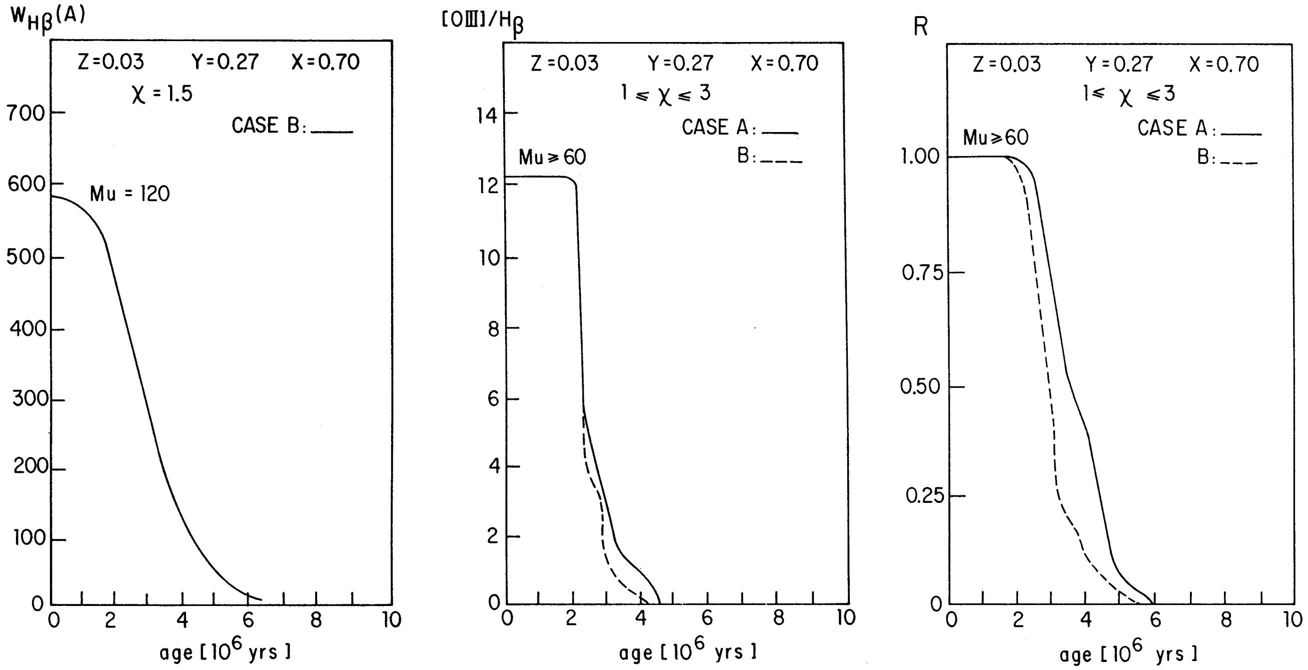


Fig. 2. Evolution of: a) WHβ, b) O III/Hβ, and c) R = VHe+/VH+, showing the influence of IMF, M and Mu. Fully developed models in CPD2.

III. RESULT FOR EXTERNAL GALAXIES

3.1 Large Magellanic Clouds

Adopting the metallicity Z = 0.008 and X = 0.742 (Peimbert and Torres-Peimbert 1974), Copetti, Pastoriza and Dottori (1985, CPD1) analyzed WHβ for 29 HII regions (Dottori and Bica 1981) and OIII/β for 25 regions (Dufour 1975; and Aller et al. 1977), arriving to the following conclusions: IMF with x = 3 ($dN/dM = M^{-(1+x)}$) does not explain 1/3 of the observed regions. The most suitable value is x = 2 or lower. For these values the IMF does not alter the range of ages obtained; Mu larger than 60$M_\odot$ are not necessary to explain the observations, and Mu lower than 30 $M_\odot$ are incompatible with many observed regions.

The maximum of star formation activity in this cycle probably occurred 5.5 E(6) years ago (figure 3) as deduced from WHβ, or 2.0 E(6) years later from [OIII]/Hβ. The difference is probably due to an underlying population contributing to the Hβ continuum lowering WHβ, to a leakage of Lyman photons, or to the observational technique of obtaining spectroscopically the line intensities (slit spectroscopy), which does not allow the measurement of all the radiation emitted by the region.

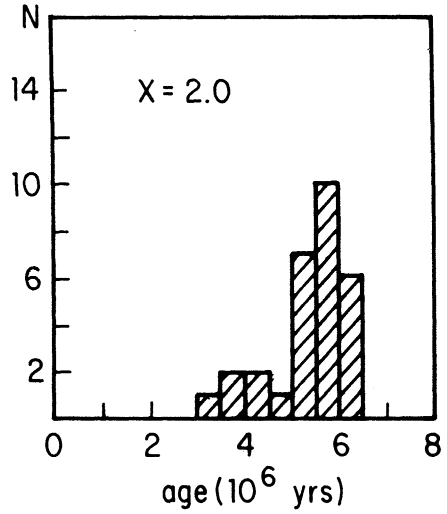


Fig. 3. Histogram of ages for the LMC for x = 2. Other values for x are shown in CPD1.

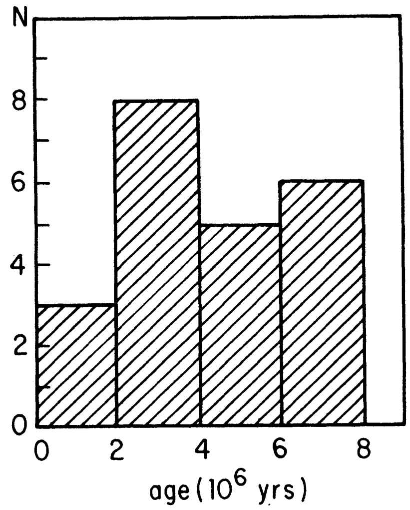


Fig. 4. Histograms of ages for BC6. x = 2 leads to a constant rate of BC6 formation.

3.2 Small Magellanic Cloud

Measures of [OIII]/Hβ for 11 regions (Dufour, 1985), and R for 3 regions (Dufour and Harlow 1977) were analyzed by CPD1 addopting Z = 0.003, X = 0.76 (Peimbert, and Torres and Peimbert 1976). The maximum activity of HII region formation probably occurred 2.3 ± 0.9 years ago. Recent measurements ofa substantially larger number of HII regions (Copetti, private communication) seems to confirm this trend.

3.3 Blue Compact Galaxies

Data on[OIII]/Hβ and WHβ for 8 Markarian objects according to Neugebauer et al. (1976), and for 14 intergalactic HII regions (French, 1980), show that an IMF with x = 2.5 explain the observations only if Mu larger than 100 M$\odot$ is assumed (CPD1). For lower values of x, x = 2 is the most probable based on arguments about homogeneity and isotropy of the space.

IV. HII REGIONS OF THE MILKY WAY

In a paper in preparation we have determined the age of HII regions from radioastronomical measurements obtained from Churchwell et al. (1974), Shaver et al. (1983), and Wink and Mezger (1983). These authors observed He+ and H+ recombination lines from which the values of R can be calculated.

As shown by Churchwell (1974), it is possible to write R × y = Q(He+)/Q(H+) since R $\cong$ 1 and y << 1. As pointed out by Seaton and Hummer (1964), and Mezger and Wink (1983), changes in R are primarily dominated by changes in Q(He+)/Q(H+) (see also Mathis 1971). The influence of the metallicity in this ratio is less than 4% (from table 2 of Rubin 1985, and the range of metallicities of the galactic disk, Shaver et al. 1983). The most important influence of the metallicity is in the opacity of the stellar atmospheres since it will cause a fall in Teff. In CPD2 it was shown that this effect can easily be taken into account since it plays the role of lowering Mu of the IMF, which makes all the models with Mu $\geq$ 40 M$\odot$ equivalent.

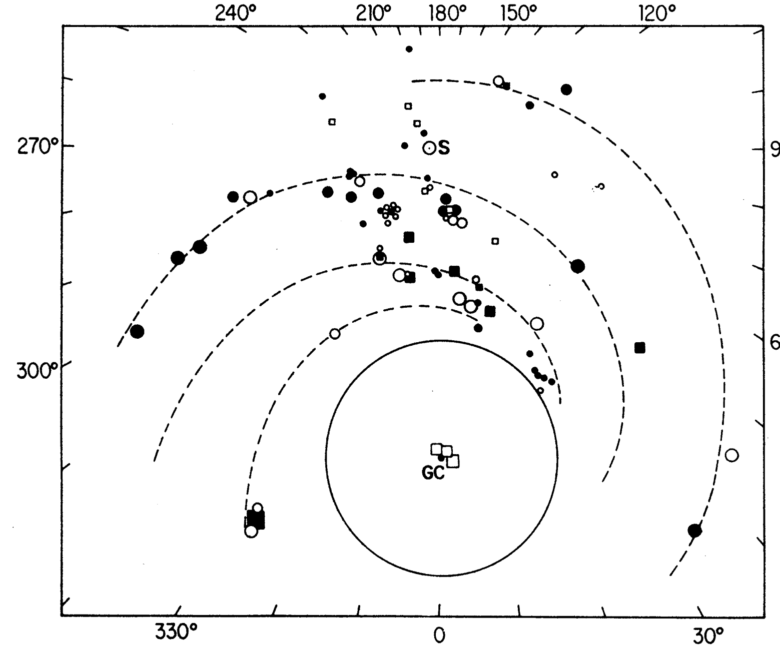


Fig. 5. The distribution of the Milky Way H II regions with measured R, according to Georgelin and Georgelin (1976) pattern. ● represent H II regions younger than 1.6 E6 yr, O(1.6E6 to 2.4E6), ■ (2.4E6 to 3.2E6) and □ older than 3.2E6 yr.

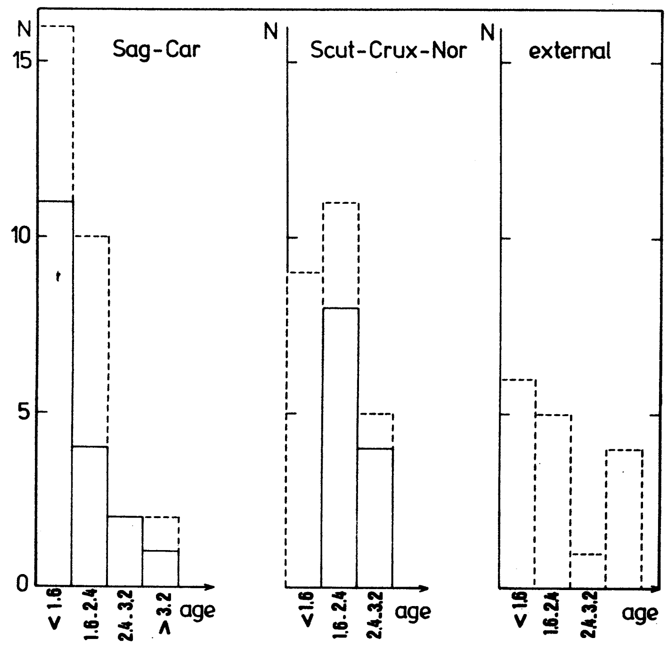


Fig. 6. The distribution of ages for the three arms. The dashed line represents regions with U ≥ Uorion (= 72 pc cm^2). The Centaurus spur is included in the Sag-Car arm (see text). The full line represents only regions with U ≥ 110 pc cm^2.

V. HII REGIONS AS DISTANCE INDICATORS

The HII regions were first used by Sersic (1960) as distance indicator. In this work and also in Sandage (1962), and Sandage and Tammann (1974), a very simple concept was used, namely the size of the three largest HII regions in a spiral galaxy is related to the luminosity class of galaxy. Kennicutt (1981) criticized this concept, showing that existing uncertainties do not make suitable the use of HII regions as distance indicators. Melnick et al. (1986) rediscussed the question making a finer analysis of the parametricity necessary to classify HII regions, concluding that 2 or probably 3 parameters are necessary to univocally specify these objects, namely a linear combination of L (Hβ), Rc (core radius) and WH$_\beta$ (emission line width), the mass to light ratio or the metallicity or a combination of both and the age.

From our point of view, HII regions need basically 2 parameters to be specified. In fact, WH$_\beta$ is a link between L(Hβ) and the mass to light ratio, which is represented in the definition of WHβ by the continuum at 4861 A. On the other hand, WHβ is related to the ratio of the size of the emitting region to that of the ionizing association (figure 7), at least for a sample including HII regions of the LMC, SMC, and M33 (Dottori and Bica 1981). More measurements are needed to extend this relation to a larger sample of HII regions. Many statistics on the size of HII regions were carried out (for example, Marcelin and Gondoin 1983), but there are not enough data on the size of the ionizing associations.

Accordingly, the effect of the aging should be taken into account when HII regions are used as distance indicators.

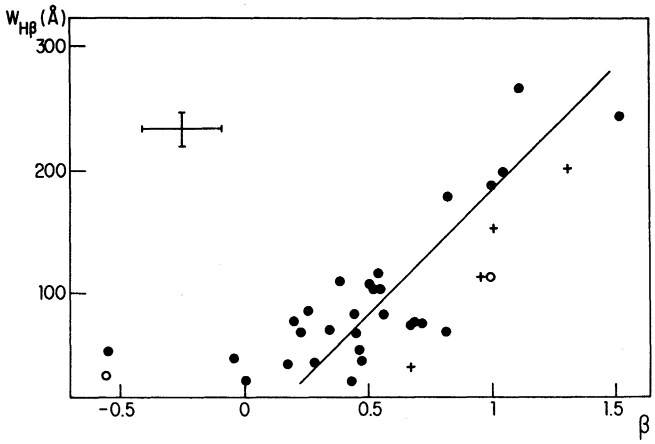


Fig. 7. WHβ vs. (2 log DHII/Dass), where DHII and Dass are the diameters of ionized region and ionizing association ● = LMC, o = SMC, and + = M33.

VI. AGING AND DETERMINATION OF METALLICITY

Generally, the determination of abundances in HII regions have to appeal to photoionization models whose numerous parameters can be reduced by assuming oversimplifications for the structure of the region (see Pagel et al. 1979 for a full discussion).

Since normally the available spectra cover wavelength ranges from about 3500 A up to 7000 A or so, the direct determination of the temperature is only possible in a few cases, due to the total absence or the weakness of the involved lines. For this reason different authors searched for metallicity dependent line ratios, with low Te dependence. Jensen, Strom and Strom (1976) suggested [OIII]/Hβ, while Alloin et al. (1979) proposed [OIII]/[NII].

These options imply practically to say that the HII regions form a one parameter family in spiral galaxies. As quoted by Pagel et al. (1979), this is not true, at least for one of the regions they have measured in NGC 300. These authors suggest as the best metallicity indicator the ratio [OII]+[OIII]/H_β, also recently indicated by Mc Call et al. (1985).

As shown in figure 8, the evolution of the [OIII]/Hβ ratio is dramatically dependent on the temperature showing only a mild dependence with metallicity. This effect can be clearly seen in figure 8a of Mc Call et al. (1985), where a variation of the Teff of the ionizing source from 37E4 diminishes the mentioned ratio by 1 dex.

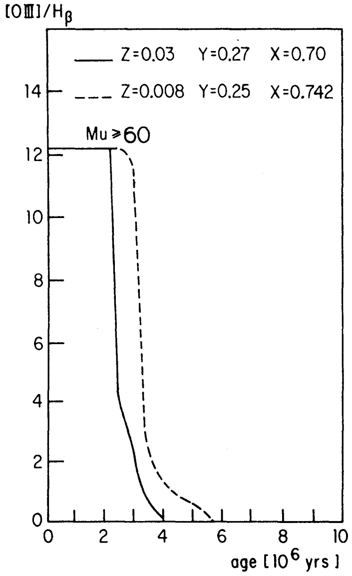
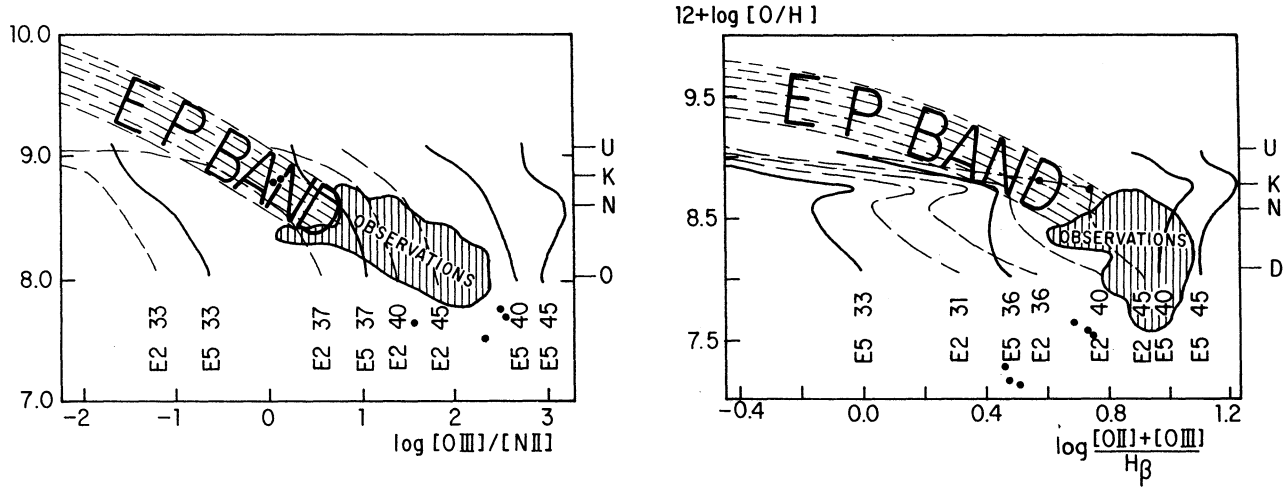


Fig. 8. The evolution of [O III]/Hβ is analyzed for two different metallicities (from CPD2) to show the relative influence of aging and metallicites.

We have also plotted the models of Rubin (1985) on a sketch of the main features of the Edmunds and Pagel (1984) graphics for [NII]+[OIII]/Hβ (figures 9a and 9b). It is easily seen that 90% of the observations are concentrated on very high values of [OII]+[OIII]/Hβ; the upper left part of EP relation is set on the basis of models, and finally the blend of the observed points (if some exist) occurs at about 12+logO/H≃8.0. According to the models of Rubin (1985), and assuming densities for giant HII regions of about 100 (Mc Call et al. 1985), these line ratios indicate Teff of the ionizing source of more than 45000 K, no matter which is the metallicity of the region. That seems to indicate a strong selection among the plotted HII regions. HII regions with such a high Teff ionizing sources will rapidly evolve (1 or 2 million years) to the left of the diagram. The question is whether the shift is at constant metallicity or not. The data on input of oxygen from evolving stars by LMDK ($M(O)/M_\odot$ = 1.8 E-2/E7 yrs) seem to set an insignificant value for the rate of enrichment during the existence of the HII region. The same can be deduced if the rate of enrichment of the disk (Peimbert 1985) is adopted. Then we can infer that the HII regions move horizontally to the left of this diagram during its evolution. Most of the dispersion is probably due to differences in Teff in the observed regions, which also makes the mean EP relation questionable.

The Rubin models set the blend of the 12+log O/H vs [OII]+[OIII]/Hβ relation near the value 8.8 of metallicity, a value substantially higher than that quoted by EP for a similar feature in their diagram.



Figs. 9a,b: Iso-temperature-density curves, from Rubin's (1985), were superposed to a sketch of the EP relation for [O III]/N II and [O II]+[O III]/Hβ in order to show the direction of the evolution. 90% of the observations quoted by EP are within the dashed areas, and the rest is shown as points. EP bend is 0.2 dex bend around EP mean relation.

The scarcity of points with [OII]+[OIII]/Hβ equal or lower than 1, even in the sample of Mc Call et al. (1985), suggests a strong selection of the observed regions. We think that two dimensional CCD frames, with narrow band filters, would be a crucial proof to show if there is not a wider sample of [OII]+[OIII]/Hβ values at a given galactocentric distance in order to avoid a selective effect, and to add a substantially larger amount of HII region per galaxy. This test, applied to [OIII]/Hβ for HII regions of M 83 (Copetti et al. 1986b), shows a larger variety of values for a given galactocentric distance than those given by Dufour et al. (1980).

On the basis of the exposed the metallicity is not the single parameter that determines the external appearance of the HII regions, as claimed by Mc Call et al. (1985). From the point of view of the observable quantities, it seems that the best combination to classify the HII regions is WHβ and the ratio [OII]+[OIII]/Hβ, taking into account that WHβ must be obtained from global measurements of the line and neighboring continuum flux, and not from slit spectroscopy.

VII. ACTIVE NUCLEI OF GALAXIES AND HII REGIONS EVOLUTION

Terlevich and Melnick (1985) have analyzed the influence of the evolution of stellar associations with stars having strong winds on the spectral characteristics of metal rich HII regions. The authors show that an association containing stars of this type, called Warmers (which can reach temperatures of more than E5 K and evolve to the left in the HR diagram), can produce a spectrum resembling that of a power law with index -1.5 for energies logν (Ryd) belonging to the interval (-0.51, 1.35) (figure 10). After 3 Myr a HII region having log Ne ≃ 3.2 and this type of ionizing association evolves to Sy2 and after 5 Myr, to Liners, or directly to Liner, depending on the intensity of the burst of star formation (figure 11).

Another support to this idea came from the IR observations. An analysis of a wide sample of Seyfert, starburst and normal galaxies (Rodriguez Espinosa, Rudy and Jones 1986), show that star formation is taking place in Seyfert galaxies of all types, suggesting a link between star formation and nuclear activity, a previous idea proposed by Weedman (1983). A comparison of the synthesis of stellar population among Seyfert, Hotspots, and normal nuclei also leads to a similar conclusion (Dottori and Pastoriza 1986).

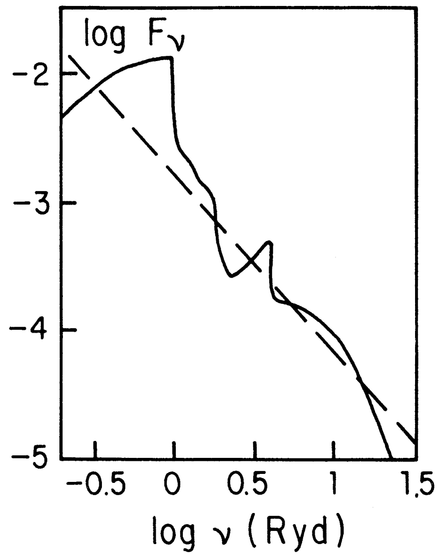


Fig. 10. The plot of the continuum generated by a ionizing association containing stars with strong mass loss and masses up to 120 $M_\odot$.

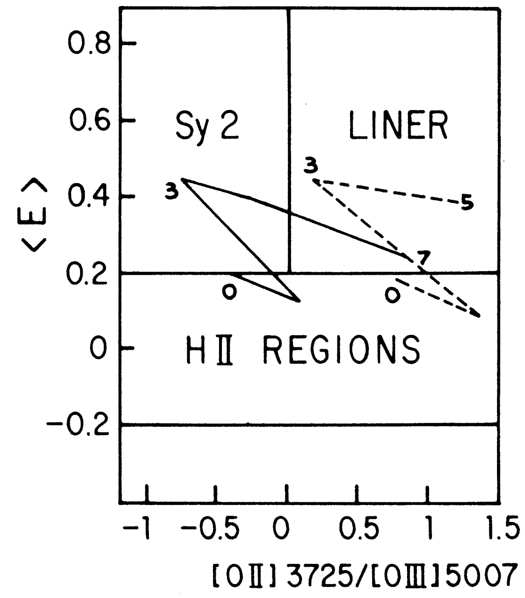


Fig. 11. The three regions in the ⟨E⟩ vs. 3727/5007 diagram, showing the evolution of a high metallicity H II region, with $n = 10^3$ part/cm^3. Full and dashed lines represent strong and weak burst of star formation, respectively. Both drawings were kindly conceded by Terlevich and Melnick.

VIII. CONCLUDING REMARKS

Along this paper we have tried to show that the HII regions are very dynamic objects, from the point of view of their evolution. It is hard to accept the idea that no evolutive differences exist among the hundreds of HII regions of a spiral galaxy when one looks at such objects. These differences cannot be ignored when HII region properties are studied.

As the physics involved in the mechanism of line emission is at the time on solid basis, people try to learn about a diversity of astrophysical problems by studying HII regions. Meanwhile, a series of problems arise due to the scarce knowledge on the hidden ionizing association. Very much is ignored about it, but through the richness of its properties it seems possible to explain complex phenomena like those of some active nuclei. The study of the HII regions by itself, or as a mean to know about other phenomena, will be very useful in Astrophysical research in the future.

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DISCUSSION

MELNICK: Terlevich, Moles y yo hemos analizado una muestra importante (∿ 50) de galaxias H II para las cuales *medimos* directamente O/H con 4363, etc. Encontramos que para un rango muy restringido de edades (alta excitación) W(Hβ) y O/H varían siempre juntos, en el sentido de que cuando O/H es pequeño W(Hβ) es grande y viceversa. Esto indica que la IMF varía con O/H y por consiguiente con W(Hβ). Este efecto puede enmascarar efectos de edad.

DOTTORI: Si pueder ser, en parte. Por eso es importante usar más de un indicador. En el caso de [O III]/Hβ o $N_{He}+H_{H}+$ no depende de la IMF.

FRANCO: ¿Tendría la densidad algún efecto en tu determinación de edades de las Nubes de Magallanes?

DOTTORI: No, porque si la nebulosa responde al caso B de Baker y Menzel lo importante acontece independientemente de la densidad, es decir, todos los fotones Ly son absorbidos.

PEIMBERT: Parecería que la diferencia entre las edades determinadas a partir del cociente de O III/Hβ y del ancho equivalente de Hβ en las Nubes de Magallanes se podría deber a un exceso de emisión en el continuo cercano a Hβ. ¿El exceso se podría explicar por la presencia de gigantes o supergigantes blancas y amarillas no considerada en los modelos teóricos?

DOTTORI: Efectivamente. También puede influir que la nebulosa tuviese pérdidas de fotones Ly (que no corresponda al caso B de BM) o que hubiese una población más vieja superpuesta. Cualquiera de estos casos afectaría W(Hβ) y no O III/Hβ.

PIŞMIŞ: En el esquema de los brazos espirales trazados por los Georgelin, hay regiones H II relativamente pequeñas. ¿Ha incluído usted en su estudio algunas de ellas? Yo esperaría diferencias sistemáticas en sus propiedades físicas, por ejemplo, abundancias químicas, con las de las regiones que delinean los brazos espirales.

DOTTORI: Nosotros tenemos que incluir sólo regiones "grandes" (entendiendo como tal, áquellas que tienen $U > U_{Orion}$). En efecto las regiones más pequeñas, fueron excluídas de la muestra. Quiero hacer dos comentarios: 1) Las regiones H II pequeñas deben estar más homogeneamente distribuidas. 2) Aunque tuviesen metalicidad diferente, nosotros no podemos detectarlo y deberíamos adoptar las metalicidades propuestas por modelos (Chiosi y Mateucci) u observadas (Shaver et al.).

POPPEL: ¿Podrías establecer la edad del brazo o ramificación local?

DOTTORI: Individualmente es muy difícil hablar de una región ya que estos son criterios estadísticos. De nuestra Figura 5 se puede ver que tenemos 2 regiones con edad menor que 2E6 años y otras 2 más viejas que 3.2E6 años.

CARRASCO: La aplicación de tu esquema evolutivo no puede ser aplicado a la mayoría de las regiones H II en nuestra galaxia, donde habría en todo caso que considerar una formación continua con un elemento de auto-inducción de formación estelar como es el caso de Orión.

DOTTORI: Yo creo que tú tendrías razón si yo usase W(Hβ), pero usando O III/Hβ estamos mirando la proporción de las diversas estrellas ionizantes formadas últimamente, ya que este cociente mide la relación de los He ionizantes a los H ionizantes.

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