Dating of H II Regions from Ionization Modeling

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Abstract. The emission-line spectrum of an H II region essentially reflects the shape of the EUV spectral energy distribution of the OB stars that ionize the gas. In principle one can use this spectrum to extract information about the age of the underlying association. In practice, a number of effects can lead to systematic errors in derived ages. The star-gas geometry is an important consideration, as it determines the ionization parameter; high-spatial-resolution imaging is thus essential to constrain the geometry. Dust grains absorb ionizing photons and decrease the Balmer equivalent widths and derived Lyman-continuum luminosity; differential extinction between stars and gas can also affect equivalent widths. Starburst synthesis models appear to over-predict the numbers of very hot Wolf-Rayet stars, especially for metal-rich starbursts; this can have deleterious effects on the modeling for such objects.

1. Introduction

The motivation for “dating” H II regions is to obtain information about the distribution of ages in the underlying young stellar population, especially in regions where the ionizing stars are difficult to resolve from the background population. By doing so one hopes to determine the details of the recent star formation history of a region and to understand better the typical duration of starburst activity. This provides important data for models of the propagation of star formation in starbursts.

Estimating ages for the ionizing stellar population of an H II region or starburst is potentially straightforward. However, there are a number of pitfalls and sources of systematic error that can produce biased results. I discuss the methodology and some potential difficulties here.

2. What Do We Really Mean by the “Age” of an H II Region?

When we talk about deriving the “age” of an H II region, what we really mean is that we are attempting to derive the EUV spectral energy distribution of the ionizing stellar population. One then hopes that the derived SED is representative of the underlying stellar population. Because of the high opacity of the interstellar medium to photons with energies $> 13.6$ eV, the EUV radiation of young OB stars is absorbed by gas in the vicinity; the gas becomes ionized and downconverts the EUV photons into lower-energy recombination-line and con-
tinuum photons, and forbidden line emission from electron-impact excitation of ions of elements heavier than helium, which escape the H II region to be observed by us.

To first order, the strength of the optical/UV forbidden lines relative to the recombination lines depends directly on the mean ionizing photon energy; the higher the mean photon energy, the higher the electron temperature, leading to stronger forbidden-line emission. Thus, as the ionizing cluster ages and the hottest stars fade away, the forbidden lines should weaken. One well-known complication is that the forbidden lines determine the nebular cooling, and so the abundance of the heavy elements is the main determinant of electron temperature. Because the far-IR [O III] lines are typically the most important coolant, a high-metallicity H II region illuminated by hot O stars may have (paradoxically) weaker optical forbidden lines than one ionized by cooler stars. In addition, the ionization parameter $U$ (a measure of the ratio of photon flux density to local gas density) affects the electron temperature. The result is that the H II region modeling problem is highly degenerate, with the ionizing SED, the ionization parameter, and the heavy element abundances all affecting the nebular excitation (Shields 1990). It is possible to explain the giant H II region emission-line sequence in a galaxy like M101 by either varying the stellar SED at fixed $U$ or by varying $U$ at fixed stellar SED (see Figure 1).

3. The H II Region Modeling Process

Figure 1 of Garcia-Vargas et al. (1997) provides an illustrative flow chart outlining the process of ionization modeling of a starburst region. One starts with a set of observed constraints on physical parameters, which are used as inputs to a photoionization model constructed with a code such as CLOUDY. These include: (1) the gas density, determined from a forbidden line ratio such as [S II] $\lambda 6717/\lambda 6731$, under the assumption that the gas is fully ionized; (2) the outer radius $R_{\text{out}}$ and the inner radius $R_{\text{in}}$, presumably determined from a high-resolution H$\alpha$ image; (3) the ionizing photon luminosity $N(L_{\text{Ly} - c})$ or $Q(H^0)$, derived from the H$\alpha$ or H$\beta$ luminosity; and (4) the nebular abundances determined from the H II region spectrum if possible. Additional inputs are the theoretical spectral energy distribution from the stellar population, and the element abundance set if one has not derived them directly from the H II spectrum. One then computes a model and compares the output spectrum with the observed spectrum. If they match, the input SED is presumed correct. If not, then a new input SED is introduced, and the process iterated until a match to the observed spectrum is obtained. A number of hidden assumptions are often involved: (i) that the stellar IMF is fully sampled. This condition may be violated for low-luminosity H II regions with a small number of O stars. (ii) That there is a single, simple geometry. (iii) That the local recent star formation history is of a simple form.

A number of observable line/ion ratios that are sensitive to the age of the stellar association are available to constrain the models.

1. Optical-UV forbidden line/Balmer line ratios: As noted above, the forbidden-to-Balmer line ratios are sensitive to electron temperature, with the caveat that they are also very sensitive to metallicity.
Figure 1. Spectral sequence for H II regions in the spiral galaxy M101 (Kennicutt & Garnett 1996). Overplotted are ionization model sequences in which the stellar effective temperature is varied at fixed ionization parameter (top panel), and sequences in which the ionization parameter is varied at fixed $T_{\text{eff}}$ (lower panel). Nebular abundances vary from 0.1 to 2.0 times the solar abundances along each sequence.

2. $\text{H} \beta$ equivalent width: The emission equivalent width of $\text{H} \beta$ reflects the EUV/optical luminosity ratio. As the age of the stellar association increases, $\text{EW}(\text{H} \beta)$ decreases. It is always observed to be smaller than predicted for a single O star of a given $T_{\text{eff}}$ because evolved massive stars and lower mass stars contribute to the continuum at 4861 Å, but not to the ionizing continuum. The predicted EW can be affected by uncertainties in the predicted numbers and colors of evolved stars, while the observed EW is reduced by the effects of dust grains (see below).

3. $\text{He}^+$/H$^+$ ratio: The ratio of ionized He to ionized H is sensitive to stellar effective temperature for O stars cooler than 40,000 K (Figure 2.5 of Osterbrock 1989). Interpretation of this ratio can be complicated by uncertainty in the He/H abundance ratio.
4. η parameter: Víchez & Pagel (1988) proposed using the ion ratio

\[ \eta = \frac{O^+/O^{+2}}{S^+/S^{+2}} \]

as a measure of the hardness of the stellar SED for H II regions. This parameter is indeed sensitive to the SED when the ion ratio can be derived directly from the spectrum. When the electron temperature is unknown and the ion ratios cannot be derived, an alternative parameter

\[ \eta' = \frac{[OII]/[OIII]}{[SII]/[SIII]} \]

has been proposed. However, the η' parameter is much more sensitive to metallicity effects (Bresolin, Kennicutt, & Garnett 1999), because each emission line can arise in zones having different electron temperatures.

One can impose additional constraints, such as the colors of the underlying continuum and the strengths of stellar absorption lines (e.g., Garcia-Vargas et al. 1997). These are sensitive to uncertainties in the stellar evolution models, and are beyond the scope of this discussion.

In principle, the problem can be solved and the age of the underlying stellar population established, given sufficiently accurate inputs. In practice, there are a number of complications that can bias age estimates.

4. Complications

4.1. Nebular Geometry

Nebular geometry is very important for constructing a detailed photoionization model of an individual H II region, as it is the principal determinant of the ionization parameter. The ionization parameter is determined by the combination of the radius parameters \( R_{in}, n_H \) and \( \epsilon \). \( R_{out} \) is then determined by the model in the ionization-bounded case, with the observed nebular size as a constraint. It is typical to assume a sphere of uniform density \( n_H \) or a “ball of filaments” of clumped gas with some \( n_H \) and a filling factor \( \epsilon \). The latter is a somewhat more realistic approximation to a real nebula which has a range of local ionization parameters.

HST imaging of nearby giant H II regions resolve these regions into a wealth of structure. The typical structure is, in fact, a bright core consisting of compact ionized shells around individual OB clusters (presumably evacuated by the combined action of radiation pressure and stellar winds), with a low surface brightness halo of multiple supershells which are probably powered by older star formation episodes. Examples can be found at [http://www.oposite.edu/pubinfo/PR/96/27.html](http://www.oposite.edu/pubinfo/PR/96/27.html) and [http://www.oposite.edu/pubinfo/PR/96/31.html](http://www.oposite.edu/pubinfo/PR/96/31.html). The 30 Doradus nebula shows similar structure.

Modeling the high surface brightness shells in these structures by filled spheres will result in too high an ionization parameter, because some of the
Figure 2. The ratio of emitted Hβ emission to that predicted from the stellar ionizing photon luminosity as a function of the nebular abundances, showing the effects of absorption of ionizing photons by dust grains. The models are for a stellar temperature of 40,000 K and assume a linear increase of the dust-to-gas ratio with metallicity.

gas is too close to the ionizing stars in the filled case. This would cause one to compensate by using cooler (older) ionizing stars and lead to too large an age. On the other hand, including the diffuse halo structure would lead to too extended a structure and a lower ionization parameter. High resolution imaging should be used whenever possible to constrain the nebular geometry.

Each H II region will have its own geometry, which will likely depend on the local star formation history and the age of the population. Therefore, a ‘one-size-fits-all’ approach based on a grid of ionization models with a single geometry is unlikely to obtain correct age estimates for any individual H II region or starburst. Ideally, one could build a gas hydrodynamical model for the evolution of the ionized region as a framework for the ionization model, but this is probably beyond present capabilities.

4.2. Dust

Dust has two major effects on the H II region spectrum. First, dust grains mixed with the ionized gas absorb Lyman-continuum radiation. Second, obscuration by dust is typically patchy; differential extinction between stars and gas can affect the emission line equivalent widths.

The absorption cross-section for standard interstellar dust grains extends well into the EUV spectral region with a peak near 17 eV. Dust grains are thus quite capable of absorbing ionizing photons in the H II regions, and in
fact can compete with H and He. When this occurs, the flux of Balmer line emission is reduced over the dust-free case. Figure 2 displays a set of ionization models showing the reduction in H{$\beta$} line emission over that expected from the number of ionizing photons for dusty H II regions. I have assumed standard interstellar grains (Martin & Rouleau 1990), with a dust-to-gas ratio that varies linearly with metallicity over the range 0.1-2.0 solar O/H. The models show that grains can reduce the emitted H{$\beta$} flux by as much as 50%. The amount lost depends strongly on the ionization parameter, increasing for higher ionization parameters. A region with high $U$ is likely to be a young one where the gas is close to the star cluster; thus more H{$\beta$} photons are missed, and EW(H{$\beta$}) reduced the most, for the youngest clusters.

Incidentally, the same phenomenon leads one to underestimate the number of ionizing photons. Therefore, claims of leakage of ionizing photons from H II regions, based on comparing N(Ly-c) from Balmer lines flux with that estimated from the OB star population, must be viewed with some skepticism.

Differential extinction between the stars and the gas can also affect EW(H{$\beta$}). Calzetti et al. (1994) found that the obscuration toward starburst clusters tended to be lower than that toward the ionized gas. They determined that, on average, $A_V$ toward the stars was about one-half of that toward the gas. This is understandable if the stars have evacuated a cavity in the ionized gas through the combined effects of radiation pressure and stellar winds. The average derived obscuration for H II regions in spirals is $A_V \approx 1$ mag. If $A_V$(stars) is only 0.5 mag, then the observed EW(H{$\beta$}) will be about 40% lower than the intrinsic value.

These results suggest that dust effects can easily cause one to underestimate the intrinsic EW(H{$\beta$}), even for metallicities as low as 0.1 solar O/H. This would lead to a systematic bias toward larger ages for the stellar population. One should therefore exercise caution in weighting EW(H{$\beta$}) as a constraint on the synthesis models.

By contrast, the effects of dust on the relative forbidden-line strengths are modest (Figure 3), except at high metallicities (Shields & Kennicutt 1995). One exception is in the case of very hot ionizing stars, where ionization of grains can lead to additional photoelectric heating of the nebula (e.g., Ferland 1999).

4.3. Wolf-Rayet Stars

How to deal with Wolf-Rayet stars in ionization models has been a problem in the past, because of the lack of information on the ionizing luminosities and shape of the EUV spectra. A great deal of progress has been made in modeling W-R atmospheres, but some uncertainties remain in connecting the atmosphere calculations to the appropriate stellar evolution state.

The situation regarding very hot W-R stars is a case in point. Spectrum synthesis models for starburst clusters predict the sudden appearance of W-R stars at an age of about 3 Myr, accompanied by a sudden jump in the flux of ionizing photons with $E > 54$ eV from hot W-R stars (e.g., Schmutz, Leitherer, & Gruenwald 1992). These hot W-R stars are expected to be more important in high-metallicity H II regions and less important at low metallicities.

Observations, however, find H II regions with nebular He II emission preferentially in metal-poor galaxies. Esteban et al. (1993) studied the central stars
Figure 3. The effects of dust grains on forbidden-line strengths in H II regions. Three sequences of models are shown, with $T_{\text{eff}} = 40,000$ K and $\log U = -3$. Solid line plus squares: dust-free models; dashed line + crosses: models with standard ISM grains; dotted line plus triangles: models with Orion-type grains. The effects of grains on the emission-line ratios are seen to be modest.

of eight W-R ejecta shells in the Milky Way. The characteristic temperatures for these W-R stars ranged between 30,000 K and 75,000 K, except for the one WO star which had a nebula exhibiting nebular He II emission. Of the six H II regions in the Local Group with He II emission, five are found in metal-poor galaxies, and only one in the Milky Way (Pakull 1991, Garnett et al. 1991). Two of these are ionized by WO stars, two by rare WN1 stars, one by the X-ray binary LMC X-1, and one by an O7 star (which is still a mystery). Except for possibly the WO stars, placement of these stars on standard evolutionary tracks is an uncertain business, and thus the predictions of nebular He II emission from starburst clusters must also be considered uncertain.

The hot W-R stars in the synthesis models can have a significant effect on the nebular spectrum, especially at high metallicities. Ionization models based on the synthesized OB clusters show a large increase in nebular excitation at the onset of the W-R phase (Bresolin et al. 1999). Metal-rich model H II region spectra at this stage have much higher excitation than observed metal-rich H II regions in spiral galaxies. Since metal-rich H II regions often show W-R star
features (e.g., D’Odorico, Rosa, & Wampler 1983), one may conclude that the synthesis models overpredict the flux of ionizing photons above 54 eV.

5. Discussion

Ionization modeling has the potential for providing important information on the spectral energy distributions and ages of the embedded stellar clusters, if one takes care in considering the effects of geometry and dust. High-resolution imaging of H II regions and starbursts is an important tool in this process, and should be obtained and employed whenever possible. The HST archives are very good place to start. More work is needed on understanding the contribution of Wolf-Rayet stars on the ionizing continuum of OB clusters, and to understand the evolutionary status of the hot W-R stars that power nebular He II emission in H II regions.

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