Age-Dating of Young Stars and Stellar Systems

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Abstract. This review addresses properties and unresolved issues of stellar systems whose ages are young in comparison with a Hubble time. In most cases, the energy production in such systems is determined by massive, short-lived stars. These stars track the most recent star-formation history in stellar clusters and galaxies. Due to their intrinsic brightness, even relatively few such stars are observable at cosmological distances. I discuss the current state of our understanding of massive stars and how uncertainties affect the interpretation of young stellar systems and galaxies.

1. Introduction: Properties of Young Stars and Populations

Kennicutt's (1998) Figure 1 illustrates the main properties — and challenges — of stellar systems hosting a young population. I will define a young population as one having an age of ~100 Myr or less. When progressing from older to younger populations, fewer and weaker *stellar* absorption lines are found in the ultraviolet (UV)/optical/infrared (IR), *interstellar* lines become stronger, and the peak of the stellar luminosity shifts into the UV. This behavior is the immediate consequence of the atmospheric and evolutionary properties of hot stars and determines the nature and validity range of available age-dating methods.

Stars with ages < 100 Myr have main-sequence masses > 5 $M_\odot$ and occupy the upper part of the Hertzsprung-Russell diagram (HRD) at luminosities $L > 10^3$ $L_\odot$. In terms of spectral types, these stars are of type OBA on and close to the main-sequence and evolve into cool and/or hot (super)giants and Wolf-Rayet (W-R) stars, depending on chemical composition and initial mass. The basic evolution can be seen in the HRD of Schaller et al. (1992). A few scaling relations in terms of mass (M) are illuminating:

- $\frac{dN}{dM} \propto M^{-2.35}$ (Massey 1998) → they are rare;
- $L \propto M^2$ (Schaller et al. 1992) → they are bright;
- $t \propto M^{-1.2}$ (Schaerer et al. 1993) → they are short-lived.

These properties of massive stars make it rather difficult observationally to disentangle the star-formation process and its duration from the evolution of a stellar

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system. Therefore determining (i) the stellar initial mass function (IMF), (ii) the duration of the star-formation process, and (iii) the age of a young stellar system are intimately connected.

1.1. Initial mass function

The upper part of the HRD is highly degenerate in terms of the relation between stellar parameters and age — even for a single stellar population. The situation is very different from, e.g., a globular cluster isochrone where most of the luminosity comes from a small mass interval close to the turn-off mass. In a typical massive-star population of single age, stars with vastly different zero-age-main-sequence masses can have similar $T_{\rm eff}$ and L and contribute to the integrated light. Any age determination is therefore dependent on an assumption on the IMF.

Since massive stars are rare and have much larger luminosities than low-mass stars, it is difficult to observe the full stellar mass spectrum in one and the same star cluster. The low-mass star content of the closest "massive"-star formation region in Orion has been studied down to $\sim$0.1 $M_\odot$ by Hillenbrand (1997). This region, however, contains only a handful of stars with masses above 10 $M_\odot$. In contrast, the R136 cluster in the LMC is rich enough for meaningful statistics above 10 $M_\odot$, but it is difficult to push the low-mass star detection limit below 1 – 2 $M_\odot$ (Hunter et al. 1995). The royal way of deriving an IMF for young populations — via clusters — is difficult or even infeasible so that IMF data are often uncertain and restricted to a limited mass range (see Leitherer 1998 and Massey 1998 for reviews). In many cases the adopted IMF is the single most important uncertainty limiting the age-dating precision (e.g., Fig. 9 of Goldader et al. 1997)

1.2. Duration of the star-formation process

The lifetime of stars with masses > 50 $M_\odot$ is < 5 Myr. Often this is not short with respect to the pre-main-sequence evolution timescale of less massive stars forming in the same region. Combined models for the main-sequence and pre-main-sequence evolution of massive stars (e.g., Bernasconi 1996) are required to interpret observations.

Young stellar systems are embedded in left-over material from the star-formation event. Stars interact with their surroundings via their ionizing and non-ionizing radiation, triggering or inhibiting subsequent star formation, or leaving the environment unaffected. Observations of local massive-star formation regions, like 30 Doradus in the LMC, suggest individual burst-like events, forming multiple clusters that can be age-dated by standard isochrone techniques. An example is Hodge 301 in the periphery of 30 Dor (Grebel & Chu 1996), which is about 20 Myr older than the central R136 cluster (Massey & Hunter 1998).

HST allows us to attempt similar analyses in galaxies tens of Mpc away. For instance, the young star-cluster system in the interacting galaxy system NGC 4038/39 has ages between 3 and hundreds of Myr (Whitmore et al. 1999). Hodge 301 ($d \approx 10$ pc) would be barely resolved by WFPC2 at NGC 4038/39's distance of 20 Mpc. How would the limited spatial information affect age-dating techniques calibrated in 30 Dor? Eventually, we would like to push the age-dating calibration to young objects at the highest possible redshift, like those seen in the Hubble Deep Field (Williams et al. 1996).

1.3. Ages of young systems

The central theme of this conference is the chronometry of stellar systems. Applied to very young systems, observations of the UV (∼1500 Å) and far-UV (< 912 Å) and a theoretical calibration of the age vs. UV luminosity are required. The age vs. optical-luminosity relation is highly degenerate due to the low sensitivity of the Rayleigh-Jeans part of the spectrum observed in hot stars (Massey et al. 1995). As a result, optical colors of young hot stars are mostly sensitive to dust reddening rather to age effects.

Direct observations of the ionizing continuum of even the closest hot stars are infeasible due to the large interstellar neutral hydrogen opacity below 912 Å (but see below for a notable exception). The high efficiency of the interstellar medium (ISM) to convert stellar far-UV continuum photons into optical and IR nebular line photons is the basis of the most commonly used technique to age-date ionizing populations: recombination lines, like Hβ, are strongly age-dependent (e.g., Figure 85 of Leitherer et al. 1999). There is, however, a caveat. The Hβ vs. age relation is essentially flat when O stars dominate but shows quite strong variations with the IMF. A strong age dependence sets in (for single stellar populations) after about 10 Myr from the onset of the star-formation event. This is when B stars provide the ionizing photons. The far-UV continuum of B stars is still quite uncertain. Observations of ϵ CMa (one of the few stars for which this measurement is possible) with the EUVE satellite by Cassinelli et al. (1995) have revealed severe discrepancies with respect to model predictions. As opposed to O stars, non-LTE and wind effects are not yet fully understood in B stars to permit a calibration of the far-UV flux vs. age relation.

2. A Few Pitfalls

Age-dating of young stellar systems invokes a combination of methods from different astrophysical fields, like the physics of stars and the ISM. Moreover, stars in the upper HRD span the full $T_{\rm eff}$ range from the hottest O3 dwarfs to the coolest M supergiants. Often the "interface" between different objects/categories is not well understood, or inconsistent definitions are adopted. In this section I address three such issues: the zero point of the metallicity scale, the spectroscopic and evolutionary definition of red supergiants (RSG), and the relation between spectroscopic (stellar surface) and evolutionary (stellar interior) properties.

2.1. The metallicity scale

The massive-star community (including the author himself) does not adhere to a rigorous definition of "metallicity". The expression *metallicity* is used (among others) for:

- the percentage (by mass or number) of all elements heavier than H or He in stellar evolution models;

- the oxygen abundance relative to the solar oxygen abundance in H II regions;
- the abundance of (mostly) α-elements relative to the sun in the atmospheres of B and A stars.

Note that metallicity is almost never defined as the logarithm of the ratio of Fe/H relative to the sun, as is customary outside the massive-star community. Partially due to this confusion, a severe inconsistency for the zero point of the massive-star metallicity scale exists.

Stellar atmosphere and evolution models adopt solar chemical composition ($Z_\odot$) with meteoritic abundances as the zero point. Depending on the specific evolution grid, abundance ratios of heavy elements may (e.g., Maeder 1990) or may not (e.g., Schaller et al. 1992) scale with Fe abundance, with obvious consequences for the chemical yields. It is now well established that the oxygen abundance of the sun is higher than that of the local ISM by about 0.2 dex (Smart & Rolleston 1997). The oxygen abundance of massive stars in the solar neighborhood agrees with that of the ISM (Cunha & Lambert 1992), as expected from the short lifetimes of massive stars. Therefore atmosphere, evolution, and population synthesis models for young stars and systems are expected to have a metallicity mismatch on the order of 60%. Any age-dating method of young systems attempting to establish relations with respect to chemical composition should be corrected for this zero-point offset.

2.2. $T_{\rm eff}$ of red supergiants

Often it is implicitly assumed that massive stars are hot. Yet they spend a few % of their lifetime as cool, core-He burning objects in the red part of the HRD. These stars are observationally identified as RSGs, or giants if they undergo core-helium or helium-shell flashes at masses below $\sim$8 $M_\odot$. I will later return to the importance of RSGs when emphasizing dust obscuration effects in young stellar systems. Here I highlight the different $T_{\rm eff}$ scales of cool stars adopted in spectral classification and in evolution models. Note that in addition to this effect, the long-standing discrepancy between observed and theoretical blue-to-red supergiant ratios is still unresolved (Langer & Maeder 1995).

Schaerer et al. (1993) and Fagotto et al. (1994) computed evolution models for RSGs with SMC composition ($\sim$1/5 $Z_\odot$). The lowest RSG temperature reached in their models is $T_{\rm eff} \approx 4000$ K. Applying a standard spectral type vs. $T_{\rm eff}$ relation, this translates into a spectral type of about K5 I. The prediction therefore is that the SMC should harbor no RSGs with spectral types later than K5, which is clearly in conflict with observations (Humphreys 1979). Most likely the discrepancy is due to a calibration of the mixing-length parameter in evolution models, which controls the extension of the outermost atmospheric layers. Efforts to calibrate this parameter observationally are underway (Keller 1999). Until consistency between the evolutionary and spectroscopic $T_{\rm eff}$ scale has been achieved, cool and metal-poor massive stars are uncertain age-indicators in young systems.

2.3. Identification of post-main-sequence stars

The degeneracy of the upper HRD was already discussed. In order to break this degeneracy, age indicators other than $T_{\rm eff}$ and L are required. The most sensitive indicators are surface abundance anomalies and increased L/M ratios, both suggesting advanced evolutionary states after extended phases of mass loss and rotation. W-R stars are the most common example: their strong stellar winds and enhanced helium, carbon, and nitrogen abundances make them useful to age-date very young populations whose most massive stars have already evolved off the main-sequence (Schaerer 1999).

Massive post-main-sequence stars carry quite age-sensitive spectral signatures so that they are commonly used to age-date young stellar systems. Yet, it is the post-main-sequence phase which is particularly uncertain in atmosphere and evolution models. A recent analysis of the most luminous emission-line objects in the R136 cluster by de Koter et al. (1997) reveals the shortcomings in our understanding of very massive evolved stars. Comparison of stellar luminosities and temperatures with isochrones suggests ages of only $1-2$ Myr, yet the stellar spectral morphologies are almost identical to those of W-R stars for which the formation time is thought to be twice this age. These "pseudo"-W-R stars are evidence for the need of improved stellar models, incorporating mixing and rotation (e.g., Langer 1998), but also for a better astrophysical interpretation of spectral morphology.

3. Age-Dating Methods

Keeping in mind the caveats of the previous sections, I will give an overview of the most popular age-dating techniques for young stellar systems. A schematic summary is in Figure 1. In this figure I have compiled eight age-dating methods and indicated the age range during which they give useful results. In the following each of these techniques is briefly discussed. Some of the speakers will cover these methods in much greater detail.

3.1. Nebular emission lines

Young stellar systems are embedded in gas. If O, B, and W-R stars are present, the gas will be ionized and excited. The observed electron temperature of the ISM results from an equilibrium between stellar heating and radiative, metallicity dependent cooling. Analysis of electron-temperature sensitive lines allows an independent determination of the stellar heating, and therefore of the stellar far-UV radiation field and its evolution with time. If the H I and He I column density is high enough and no ionizing photons escape, and in the absence of dilution by an underlying population, H and He recombination-line fluxes are useful age indicators as well (García-Vargas 1996; Stasińska 1996).

The age range for which this technique is sensitive coincides with the evolutionary timescale of O stars, i.e. $\sim$10 Myr for a single population. Evolutionary synthesis calculations coupled to photoionization models predict strong variations of the far-UV radiation field, in particular when hot stars with strong winds appear (e.g., Stasińska & Leitherer 1996; Crowther et al. 1999; Schaerer & Stasińska 1999). Different models seem to converge in their predictions and

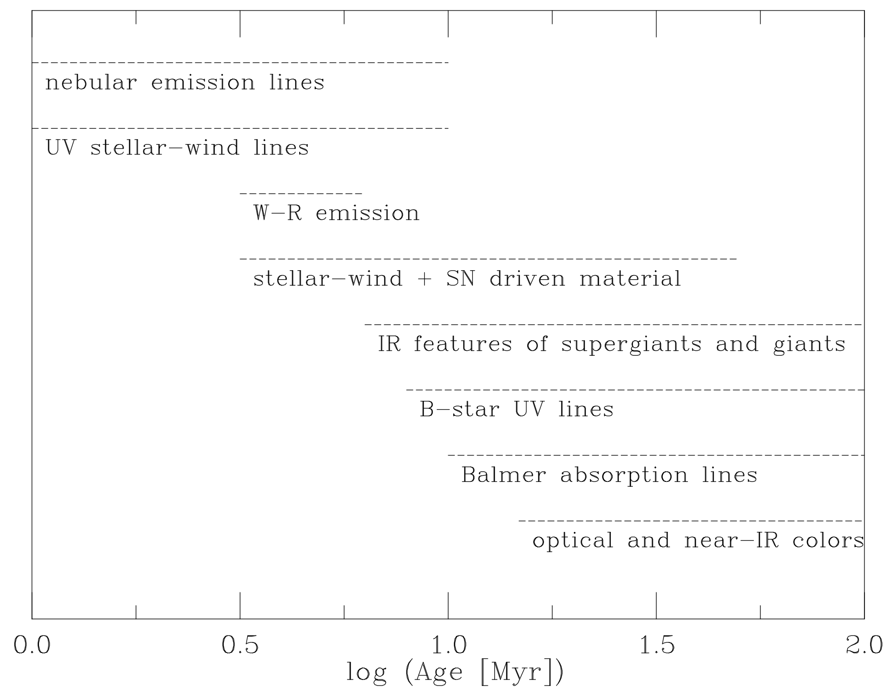

Figure 1. Common methods to age-date young stellar systems. The dashed lines indicate the age range over which the methods are reliable.

with observations longward of the He° edge but discrepancies exist around and below the He^+ edge (Bresolin et al. 1999). Possible reasons include the interfaces between atmosphere and evolution models during the W-R phase.

If non-thermal heating is not negligible, for instance when strong stellar winds and supernovae are present (cf. Section 3.4), the emission-line spectrum may become affected by shocked gas. Viegas et al. (1999) suggested that some line ratios in IR-luminous galaxies are determined by shocks rather than by stellar photoionization.

3.2. UV stellar-wind lines

The wavelength region between 1200 Å and 2000 Å is dominated by stellar-wind lines of, e.g., C IV λ1550 and Si IV λ1400, which are the strongest features of hot stars in a young population (e.g., Robert et al. 1993; Leitherer et al. 1995). In contrast, the optical and IR spectral regions show few, if any, spectral signatures of hot stars, both due to blending by nebular emission and the general weakness of hot-star features longward of 3000 Å.

Hot-star winds are radiatively driven, with radiative momentum being transferred into kinetic momentum via absorption in metal lines, like those observed in the satellite-UV. Therefore the stellar-wind dominated phase is essentially identical to the nebular phase (see Figure 1). Since the stellar far-UV radiation field softens with time for an evolving single-star population, the wind strength decreases, and the lines change from being P Cygni wind profiles during the first few Myr to purely photospheric absorption lines after tens of Myr. This is

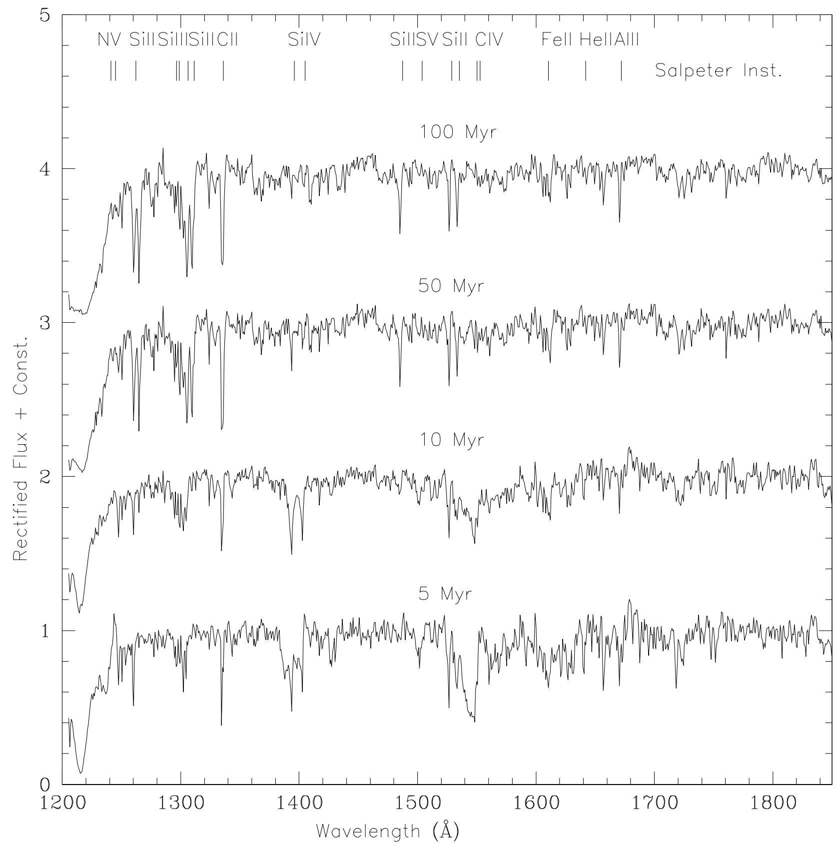

Figure 2. Simulated UV spectra of a single stellar population of age 5, 10, 50, and 100 Myr. $Z_\odot$ and Salpeter IMF between 1 and 100 $M_\odot$.

illustrated in Figure 2 (from de Mello et al. 1999). If O stars with zero-age-main-sequence masses above 30 $M_\odot$ are present, C IV shows a P Cygni profile. In the absence of such stars (after 10 Myr), the line becomes weaker and disappears due to the changing wind density and ionization conditions. Around 100 Myr, the population is B-star dominated, and singly and doubly ionized transitions of C and Si serve as age indicators.

An important application of this method is at redshift > 2 for which the wavelength region shown in Figure 2 becomes accessible to large ground-based telescopes. Currently the most severe limitation of this technique is the lack of metal-poor models and libraries (cf. Heap & de Koter 1995).

3.3. W-R emission

The only unblended *stellar* features observable in the integrated optical spectrum of an O population are normally from W-R stars. As pointed out before, W-R stars are extremely sensitive chronometers but careful calibration of atmosphere and evolution models is required. The onset and termination of the W-R phase is subject to debate (see Leitherer 1999). In Figure 1 this phase lasts from 3 to

6 Myr but metallicity, strong mass-loss in the pre-W-R phase, and mass transfer in close binaries can prolong or decrease the W-R phase.

Given these uncertainties, one may wonder why W-R stars could be better age tracers than other methods. W-R stars become important, e.g., when nebular lines cannot be trusted as age indicators. One application are Seyfert2 galaxies, some of which are suspected to have young hot stars as the source of their optical/near-IR continuum. OBA stars have few suitable lines to prove or reject this hypothesis. The nebular emission lines are not predominantly due to stellar photoionization, making them unsuitable as a hot-star indicator. Therefore the discovery of W-R features in Mrk 477 (Heckman et al. 1997), Mrk 1210 (Storchi-Bergmann et al. 1998), and other Seyfert2 galaxies is significant.

Even in the absence of an AGN, nebular properties are sometimes difficult to interpret in terms of the ionizing population. "Photon counting" is complicated by photon leakage and absorption of photons by dust. The latter effect may be important in IR-luminous galaxies whose ionizing radiation field is known to be particularly soft (Goldader et al. 1997). Detection of a W-R population in these galaxies would indicate a very young age with very massive stars present.

3.4. Stellar-wind and supernova driven material

A few percent of the total radiative stellar luminosity of a young population is converted into mechanical luminosity via stellar winds and supernovae. Integrated over their lifetimes, the energy release by stellar winds is comparable to that of a supernova event: Mass-loss rates of 10^{-5} $M_\odot$ yr^{-1} and wind velocities on the order of 10^3 km s^{-1} result in mechanical energies around 10^{51} erg over 10^7 yr. Eventually, thermalization occurs due to interaction with the surrounding ISM. On a grand scale, the ultimate fate of a stellar, radiatively driven wind is to become a galactic, coronal wind.

Hydrodynamic models for the resulting wind- or supernova-driven bubbles (Chevalier & Clegg 1985) or, on larger scale, for galactic superwinds (Suchkov et al. 1994) predict well-defined relations between age and morphology of the outflow. Tests using bubbles around OB associations in the LMC by Oey (1996) indicate fair agreement between theory and observations. Despite uncertainties in the derived ages, this technique is often one of the few available to age-date starbursts in very luminous, dust-obscured galaxy nuclei (Heckman et al. 1990).

3.5. IR features from supergiants and giants

After about 5 Myr the most massive stars of a single population evolve toward cooler temperatures forming RSGs. The RSG continuum and lines will dominate the red and near-IR for the following tens of Myr. Since RSG wind densities and surface gravities are orders of magnitude lower than in their hot evolutionary progenitors, narrow ($\sim$2 km s^{-1}) photospheric lines can be observed in individual stars. In an unresolved population, these lines allow a velocity dispersion measurement, and therefore a determination of the cluster mass (Ho & Filippenko 1996).

More relevant for the theme of this conference is the shift in wavelength of age-sensitive lines from the UV to the IR that occurs with the appearance of RSG which often dominate the near-IR light. Contributions from less luminous — but more numerous — giant stars must be carefully evaluated since both stellar

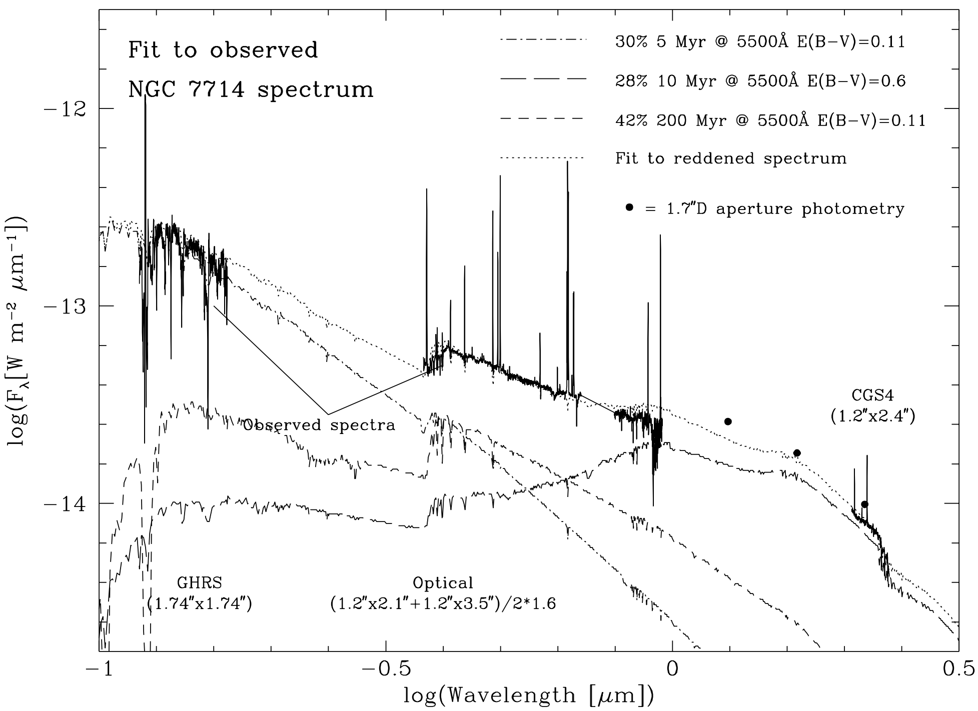

Figure 3. UV-optical-IR spectrum of the starburst nucleus in NGC 7714. Model fits to the individual populations suggest that 90% of the UV light is obscured by dust.

components can be important, depending on the type of population (Rhoads 1998). Examples of RSG-sensitive lines are the Si I and CO features in the H and K bands (Origlia et al. 1993). Populations embedded in dust can be observed in these lines with dust obscuration reduced by a factor of 10 relative to the V band.

In Figure 3 I have plotted UV, optical, and near-IR spectra of the starburst nucleus in NGC 7714, all obtained through similar aperture sizes (from Goldader et al. 1999). Analysis of the individual populations suggests that the RSG population seen in the IR is heavily obscured. The associated hot-star population, after dereddening, would be ten times more luminous than the actually observed population at 1500 Å. In other words, even after reddening correction, the observed UV flux accounts for only about 10% of the actual luminosity — 90% of the UV light is totally hidden from view. NGC 7714 is rather typical in this aspect: Heckman et al. (1998) found that on average only 10% of the generated non-ionizing UV photons leak out of local starburst galaxies. Age-dating young systems in the UV, and even the optical, will measure the tip of the iceberg, leaving open the age-relation between the obscured and unobscured populations.

3.6. B-star UV lines

B stars, like O stars, have few spectral lines in the optical and near-IR so that the wavelength region of choice is the UV. Most of the discussion in Section 3.2 applies to B-star lines as well. B stars, in comparison with O stars, have weaker winds. Therefore their P Cygni profiles are less conspicuous in a UV spectrum of a population. Furthermore, the lines are narrower due to lower wind velocities, and they come from lower ionization potentials; C II λ1335 is one of the strongest B-star wind lines (see Walborn et al. 1995). This makes them often hard to distinguish from ISM lines, which tend to have similar ionization ranges, in particular if observed at low spectral resolution.

In addition to wind lines, B stars have numerous relatively strong photospheric absorption lines in the UV region. These lines arise from excited levels and can therefore not be produced in the ISM. A typical example is the Si III multiplet around 1300 Å (Figure 2). The strong age dependence makes several of these lines useful clocks for populations of 100 Myr and older. Consider, for instance, the variation of the Si III λ1300/Si IV λ1400 ratio between 5 and 100 Myr in Figure 2 (see also de Mello et al. 1999)

3.7. Balmer absorption lines

The stellar hydrogen lines are among the strongest absorption features for a young population *at any age* due to the ubiquitous presence of H. During the first $\sim$10 Myr in the evolution of a single population most hydrogen absorption lines are strongly blended by nebular emission and not very useful for age determinations. After about 10 Myr, the ionizing O stars disappear and a hydrogen absorption spectrum appears which increases with age, reaching maximum strength around a few hundred Myr when A stars dominate the spectrum (e.g., Bica et al. 1994).

Balmer lines were used to age-date compact star clusters in the cooling-flow galaxy NGC 1275 (Brodie et al. 1998), the merger system NGC 7252 (Schweizer & Seitzer 1998), and the starburst M 82 (Gallagher & Smith 1999). Accurate ages are essential to tackle the question if these clusters are progenitors of present-day globular clusters. Obtaining cluster spectra reaches the limits of major ground-based telescopes so that strong features, such as the Balmer lines are the method of choice. Colors are often affected by extinction corrections and crowding. The Balmer-line method suggests ages between tens and hundreds of Myr. Balmer lines are costly in terms of observing time since the removal of nebular contamination requires high spectral resolution, but they have the advantage of being (almost) independent of metallicity and unaffected by reddening (see also González Delgado et al. 1999). The Balmer jump shows a similar behavior with age. It can be measured with intermediate-band filters, and thus may open the way for further age-dating surveys.

3.8. Optical and near-IR colors

Colors are the prime age indicators in intermediate and old stellar populations. Reddening and the optical color degeneracy of hot stars limit their use to ages of more than about 20 Myr. There is very little metallicity dependence in young systems due to the lack of strong metal lines in the optical and near-IR. Metallicity does enter via evolution models when RSGs affect the colors (between

10 and 50 Myr). As pointed out by Mayya (1997) and Origlia et al. (1999), this particular model prediction is not correct due to wrong RSG parameters in stellar evolution models for metal-poor populations.

The main challenge in interpreting colors of young systems is to break the *age-reddening degeneracy*. The reddening vector is parallel to the isochrones in most color-color diagrams, and the reddening correction uncertainty is often much larger than the desired precision of the age determination (see, e.g., Figure 4 of Johnson et al. 1999). A color combination minimizing this degeneracy is $(B - H)$ vs. $(H - K)$ (Devost 1999). It is worth reminding the reader that reddening corrections are not only an issue for interpreting colors but also for line equivalent widths (e.g., Hβ), as the obscuration of stars and gas is not the same in a young population.

4. Highlights

Rather than giving a summary, I highlight three issues to reflect upon:

- *Observers and theoreticians often define stellar clocks differently.*
- *The most sensitive clocks are those which are poorly understood.*
- *Age-dating young systems requires synchronization of stellar and interstellar clocks.*

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