A&A 580, L5 (2015)
DOI: 10.1051/0004-6361/201526588

Astronomy & Astrophysics

Letter to the Editor

Precision age indicators that exploit chemically peculiar stars

Guy Worthey

Washington State University, 1245 Webster Hall, Pullman, WA 99164-2814, USA
e-mail: gworthey@wsu.edu

Received 22 May 2015 / Accepted 13 July 2015

ABSTRACT

Context. The integrated light of distant star clusters and galaxies can yield information on the stellar formation epochs, chemical abundance mixtures, and initial stellar mass functions, and therefore improve our understanding of galaxy evolution.

Aims. We would like to find a way to improve the determination of galaxy star formation history from integrated light spectroscopy.

Methods. Several classes of chemically peculiar (CP) stars arise during the course of normal evolution in single stars and noninteracting binary stars. An aging stellar population has periods of time in which CP stars contribute to the integrated light, and others in which the contributions fade. The HgMn stars, for example, occupy a narrow temperature range of 10 500 to 16 000 K, which maps to a narrow range of ages. Wolf-Rayet stars, He-poor stars, Bp-Ap stars, Am-Fm stars, and C stars all become very common in a normal stellar population at various ages between zero and several Gyr, fading in and out in a way that is analogous to features used in stellar spectral classification. We examine population fractions and light fractions in order to assess the feasibility of using CP stars as age tracers.

Results. Even though CP stars do not usually dominate in number, there are enough of them so that the CP spectral features are detectable in high-quality integrated spectra of young and intermediate age stellar populations. The new technique should be calibratable and useful. Furthermore, using CP signatures as age dating tools sidesteps reliance on photometry that is susceptible to dust and Balmer features that are susceptible to nebular fill-in.

Key words. stars: chemically peculiar – stars: evolution – galaxies: stellar content – galaxies: starburst – galaxies: evolution

1. Introduction

Tracing stellar population age by integrated light is a mainstay of galaxy evolution interpretation. Somewhat ambiguously, yet still of great value, blue photometric colors generally indicate galaxies with ongoing star formation, while red colors indicate galaxies that have not formed significant numbers of stars in the last few hundred million years. A technique that often gives higher precision is using Balmer feature strengths in young populations (Levesque & Leitherer 2013) or in old ones (Trager et al. 2000). While these considerations yield a mean, light-weighted age fairly readily, uncertainties remain. First, since all Balmer features measure approximately the same thing, namely stellar temperature, they are equivalent to one measureable quantity, and a mean age is all one can realistically hope to achieve, which is rather far from the ultimate goal of uncovering the star formation history. There are also astrophysical degeneracies such as age-metallicity degeneracy at old ages (Worthey 1994) and age-initial mass function degeneracy and age-interstellar medium degeneracy at young ages (Leitherer 2005).

The motivation for this paper is to highlight a new strategy for age dating stellar populations using only high-quality integrated light spectra. Since the method relies on chemically peculiar (CP) stars, a description of the subtypes most likely to be useful is in order.

Wolf-Rayet (WR) stars are mass-losing upper main-sequence stars. Because of their extreme winds and subsequent mass loss, portions of the WR stars that have undergone nuclear processing are exposed and they become CP and exhibit emission line features in their spectra. The notable bump in the λ = 4640–4690 Å region (Conti 1991) is seen in a morphologically heterogeneous handful of starbursting galaxies known as Wolf-Rayet galaxies (Schaerer et al. 1999). This class of galaxies is already being modeled and studied (Leitherer et al. 2014).

Moving to cooler classes of CP stars, in stars with slow rotation and radiative atmospheres a combination of species-dependent gravitational settling and radiation pressure can lead to heavy species levitating to the top of the photosphere, causing strong alterations in the observed spectrum (Michaud 1970) that explain at least some of the large numbers of peculiar spectral types among BAF stars (Cowley et al. 1969). We are interested in the numerically most common subtypes. They are He-weak (CP4) stars that span spectral types B2-B8, HgMn (CP3) stars that span spectral types B6-A0, Bp-Ap stars (CP2) that span spectral types B6-F4, and Am-Fm stars (CP1) that span spectral types A0-F4 (Smith 1996); the designations in parentheses are from Preston (1974).

The diffusion (heavy species levitation) timescales are short compared to the evolutionary timescales (Michaud et al. 1976), and so it is probably a combination of binarism, rotation, and magnetic fields that control the levitation CP phenomenon (Bailey et al. 2014). The fraction of CP stars as a function of age cannot at present be predicted ab initio. However, the stars are all main sequence or near main sequence, and are therefore amenable to precise empirical scrutiny.

It is known that the various subtypes lie in well-segregated temperature regimes (North 1993; Smith 1996), which is a crucial aid to their use as extragalactic age indicators. The levitating CP stars are common. HgMn stars account for 15% of B8 stars, and over 60% of A6 stars are Am or Ap (Smith 1996). For stellar populations at the correct ages, their optical-UV spectral features should be strongly influenced by chemical peculiarities.

Finally, coolest of all, C stars arise late in the lives of 1.5−4 $M_\odot$ stars on the asymptotic giant branch where a third dredge-up convects sufficient C to the surface to tip the number ratio C/O > 1 (Marigo et al. 2008). The mass range translates to population ages between 0.5 and 5 Gyr for heavy element abundances typical of the Magellanic Clouds. When C begins to dominate, the spectra of these giants transform from being shaped primarily by H_2O and TiO molecular features to CN, C_2, CH, and similar, while CO remains strong. These stars are very cool (Bergeat et al. 2001), but are bolometrically the brightest stars in the population. A measure of the ratio of TiO to C_2 features, for example, would readily give an estimate of the C star fraction, and therefore additional age information. Unlike WR or levitating CP stars, for which blue or UV spectra are most revealing, the telltale spectra for C stars should be in the red or infrared.

In this Letter, we let the topic of WR stars stand as sufficiently demonstrated, in the sense that it is clear that WR features can be seen in the integrated spectra of some galaxies, and that seeing such features provides additional leverage on the ages of the youngest stars present in the observed galaxy. Section 2 discusses the feasibility of HgMn stars as age indicators. Section 3 gauges the observable effect of C stars on intermediate age stellar populations, and Sect. 4 briefly discusses the other CP classes. Section 5 extends the discussion to the future of this technique, outlining the groundwork necessary to make it viable.

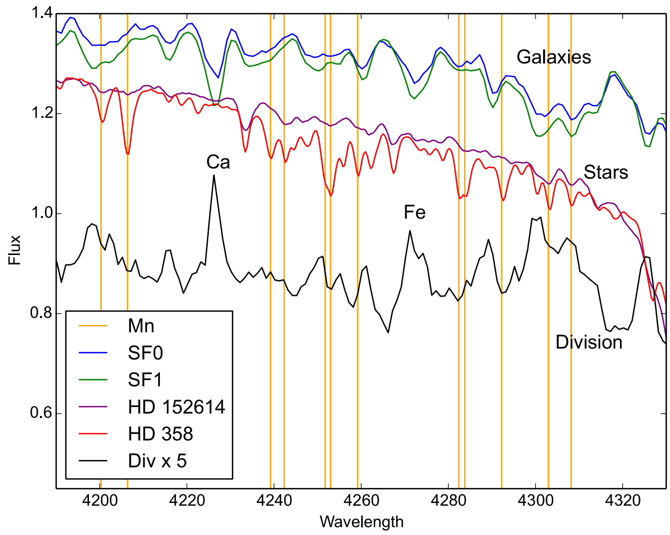

Fig. 1. Portion of the spectrum between Hδ and Hγ. Average galaxy spectra of categories SF0 (blue) and SF1 (green) from Dobos et al. (2012) and their division scaled about the average by a factor of five (black) are shown along with normal B8 star HD 152614 (ι Oph; purple) and HgMn star HD 358 (α And; red) from Valdes et al. (2004). Wavelengths of Mn transitions (Kramida & Sansonetti 2013) are marked as orange vertical lines. The feature of keenest interest is that the four strongest Mn features in HD 358 appear as small differential absorptions as one goes from SF1 to SF0 average galaxies.

2. HgMn stars

According to Smith (1996), HgMn stars span spectral classes A0 through B6 and temperatures from 10 500 to 16 000 K. This translates to main-sequence turnoff masses in a range from 3 to 4 $M_\odot$, and that in turn translates to a narrow age range of 75 to 150 Myr at solar metallicity (Bertelli et al. 1994). While they exist in the stellar population, their number fraction apparently hovers near 10% of B7, B8, and B9 stars (Smith 1996).

Their spectral classifications (and names) rest upon a Hg II feature at λ3984 and Mn II features at λ3944, λ4137, λ4206, and λ4282. There are a smattering of HgMn stars in the Coude Feed Library (Valdes et al. 2004), and we investigated example stars to get a better idea of the true spectral signature for this CP subclass, finding several more strong Mn features. An illustrative pair of CP and normal stars is illustrated in Fig. 1, slightly smoothed, along with wavelengths from Kramida & Sansonetti (2013).

Also plotted in Fig. 1 are two average blue galaxy spectra from Dobos et al. (2012), their two bluest categories, SF0 and SF1. The Mn features are not obvious until the bluest average (SF0) is divided by the next (SF1), and then the four strongest Mn features seen in the stars also show up as small extra differential absorption. Most metallic features should be fading as the average stellar population becomes hotter, as seen by the indicated Ca and Fe features, and Mn is never strong except in HgMn stars, so getting more Mn absorption when moving to hotter stars is remarkable. In combination with the fourfold wavelength coincidence, this is strong evidence that the HgMn spectral signature has been detected in aggregate galaxy spectra. It follows that the HgMn phenomenon can be used in extragalactic age dating once appropriate models are constructed.

3. C stars

The stellar evolutionary calculations of Marigo et al. (2008) include the surface C/O abundance of AGB stars. We included them in the Worthey (1994) population models, along with synthetic C-rich spectra from Aringer et al. (2009) where we imposed a correction for self-extinction of $A_V = (2800 - T_{\rm eff})/800$ for stars with $T_{\rm eff} < 2800$ K in order to compensate for the lack of dust in that particular grid and make it come into agreement with the Bergeat et al. (2001) color temperature relations.

The low-resolution spectra from these calculations are displayed in Fig. 2 for simple stellar populations of solar abundance and ages 0.5, 1.0, and 2.0 Gyr, and then displayed again with the C stars replaced by M stars of the same atmospheric parameters. Redder than R band, the spectral changes are obvious.

For the purposes of this Letter, we do not adjust the models for recent suggestions for downward revisions to the predicted number of C stars (Girardi et al. 2013); a glance at Fig. 2 is enough to understand that factors of two or three are not sufficient to erase the C star spectra signatures, many of which exceed 25% in that figure. Ongoing discussion of the numbers, luminosity functions, and frequencies of C stars are healthy steps toward using them as age indicators.

One additional caution about C stars is that they are rare, evolved stars susceptible to stochastic counting effects that can have effects on integrated properties in some cases (Santos & Frogel 1997) though entire, large galaxies are probably immune from stochastic effects. The other, bluer CP stars discussed in this Letter are not susceptible, because they are main-sequence stars and are therefore very numerous.

4. Remaining CP categories

According to North (1993), who studied CP stars that are members of open clusters, Si-strong and He-weak stars (also known as hot CP2 stars or Bp-Ap stars) are already present at the 5% level in clusters of age 10 Myr, though they are not located at the main-sequence turnoff (MSTO) at that age, and they hover at 10% frequency thereafter until disappearing at around 500 Myr.

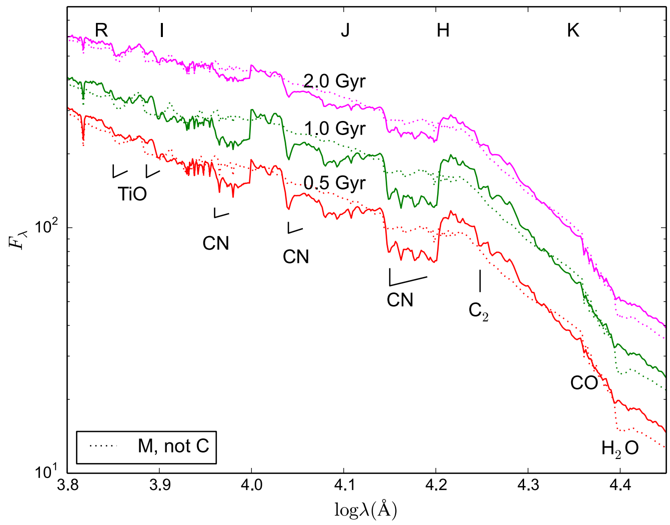

Fig. 2. Simple stellar population model spectra at solar abundance and three ages, 0.5, 1.0, and 2.0 Gyr, each age labeled on the plot. Carbon stars are included (solid lines) or M stars are substituted for C stars (dashed lines). While CO absorption stays about the same for both cases, there is marked and opposed variation in the H_2O and TiO features of M stars compared to C_2 and CN features due to molecular balancing.

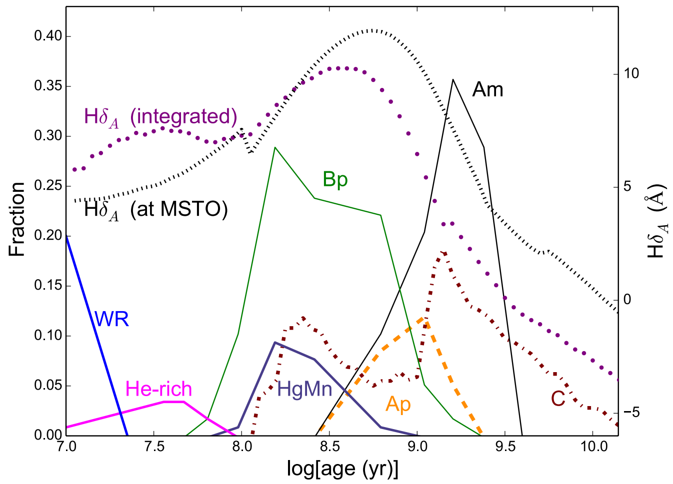

Fig. 3. Schematic time line showing the age indicators. The Hδ_A index (Worthey & Ottaviani 1997) for the hottest star near the main-sequence turnoff (MSTO; black broken line) and for the integrated light of the simple stellar population of solar abundance (purple dots) refer to the right-hand axis. The remainder of the lines refer schematically to the left-hand axis. The Wolf-Rayet fraction (blue line) is entirely schematic. The lines for He-rich (magenta line), Hg-Mn (slate blue line), Bp (thin green line), Ap (dashed orange line), and Am (thin black line) stars are estimated from data in North (1993) with approximate stellar mass converted to a MSTO age and an overall normalization estimated from Bright Star Catalog classifications (Smith 1996). The line for C stars (dash-dotted maroon line) is from the models, and therefore refers to the theoretical predictions of Marigo et al. (2008), and is expressed as the fraction of C stars compared with the total number of AGB stars in the population. Smith (1996) finds significantly more Am and HgMn stars and somewhat fewer Bp stars than North (1993). In this figure, the Bp star category includes both Si-strong and He-weak types, which transition at a boundary approximately where HgMn stars peak. There is probably a sharper boundary between Ap and Bp than is evident in this figure, and the old-age Am boundary is uncertain due to scarcity of data.

The cooler CP2 stars that show enhanced Sr, Cr, and Eu appear at ~60 Myr and disappear at ~1 Gyr, never exceeding 5% frequency. Am stars (CP1) also appear at ~60 Myr at the 5% level (again, not at the MSTO), but just as the hot CP2 stars are fading at 500 Myr, the Am frequency appears to rise to 25% before falling off again at or after 1 Gyr. North's study is limited especially at the old end by a dearth of clusters.

These CP categories are shown in context with the others and with the rise and fall of the Balmer feature index Hδ_A in Fig. 3, which is an imprecise amalgamation of data and models. If we can properly calibrate all the CP subtypes and then detect their presence in integrated light, however, it follows that we can use them as precise age dating tools.

5. Discussion and conclusion

Considering the comings and goings of hot and cool CP2 stars, Am stars, HgMn stars, WR stars, and C stars, we see that some event or other happens every few tenths along a log t timeline (Fig. 3). This excellent "age resolution" is improved by including time-tested photometric colors and Balmer features. Given this new wealth of observational signatures, we can realistically consider deriving star formation histories from integrated light alone.

The observability of the CP age indicators is good, though high signal-to-noise ratio (S/N) is required for security. To estimate S/N requirements, we suppose that a CP star has an increase (or decrease) in its various absorptions of equivalent width $W_{\rm CP}$. That equivalent width is attenuated by stars in other parts of the HR diagram by a factor $f_{\rm pop}$ and by the numerical rarity of the CP star category $f_{\rm CP}$ so that the measured equivalent width is $W = W_{\rm CP} f_{\rm pop} f_{\rm CP}$. The uncertainty depends on S/N as $\sigma(W) = \sqrt{2}(\Delta\lambda - W)/(S/N)$, where $\Delta\lambda$ is the window over which the measurement is made, and the S/N refers to that same spectral window (Vollmann & Eversberg 2006). For a single, weak absorption, if a particular CP type is located at the main-sequence turnoff and has 10% frequency ($f_{\rm CP} = 0.10$) and has a spectral feature that is 95% of continuum and about $\Delta\lambda = 4$ Å wide ($W_{\rm CP} \approx 4(0.05) = 0.20$ Å), and if the turnoff stars contribute half the light in the blue ($f_{\rm pop} = 0.50$), then $W \approx 0.01$ Å. In that case, one would want a continuum $S/N \sim 2000$ over the wavelength span of the weak feature for secure detection. This worst-case requirement is greatly lessened in the usual case where many (if not hosts of) absorption features contribute to the signal, and also many signature absorptions (especially H, He, and Ca) are much stronger than 5% deep.

The S/N requirement also lessens in the UV, where the absorptions are stronger and the dilution by non-turnoff stars lessens. Working to increase S/N requirements is that CP stars often have depressed continuum in the UV, but it still works out to be a net positive gain as long as the line absorption increases faster than the continuum depression.

The observability as a function of CP type depends on the number and strength of the absorption features in the observed spectral window. Roughly speaking, however, relative to Hg–Mn stars, all the types we mention will be easier to observe. He-rich stars are characterized by a good collection of strong He lines throughout the blue and visual, weak H lines, and all but absent C lines, the combined equivalent widths of which should comfortably overwhelm the Mn lines we point out for HgMn stars. Bp and Ap stars are the more extreme cousins of Am stars, and show strong Si, Sr, Cr, and Eu, again with a healthy sum of equivalent widths over the many features present.

Am stars have a weak Ca K feature combined with strong metal lines, including Fe, and therefore again containing a very healthy sum of total absorption. In the Am case, complete disambiguation of the Am signature may require measuring Ca K accurately, worrisome because it is a single spectral feature. To ease the worry, however, we note that this is a strong absorption feature with $\Delta W \sim 1$ to 2 Å when the Am peculiarity is imposed.

We did not list some CP categories because of their relative rarity. The small number of CP stars lessens their influence on integrated light. These include λ Boo stars, metal-poor CH stars, and stars that are CP because of binary evolution effects such as barium stars and Sr4077 stars. These stars should be kept in mind for the future, as their spectral signatures could, firstly, slightly blur the results from the more common CP varieties, and, secondly and more positively, some day enable a direct measurement of binary fractions in external galaxies.

The calibration of the technique is in its infancy and needs much more work. Spectral libraries should be built with explicit inclusion of sequences of CP stars. If synthetic stellar libraries are employed, new grids will have to be computed to accomodate the altered abundances, but a more systematic study will be needed to specify the abundance patterns that should be synthesized as representative of each class of CP stars.

Spectral libraries should be extended to the UV, if possible, because the spectral signatures of chemical peculiarity become stronger (Fuhrmann 1989a,b) and the light fraction contributed by stars near the main-sequence turnoff increases, though these trends are somewhat attenuated by a lowering of the UV continuum in CP stars. Going to the UV is also convenient for application to high-redshift galaxies.

For evolutionary population synthesis, the numbers and temperatures of stars need to be known with confidence as a function of age and heavy element abundance. In this regard, *Gaia* distances to thousands of nearby CP stars will be very helpful regarding temperature spreads and number fractions, but continued survey work in open clusters, associations, moving groups, and well-studied local group galaxies for CP stars is even more essential because the ages and initial metallicities can be known (Landstreet et al. 2007).

In conclusion, this Letter presents an outline for a technique to unravel age structures in the integrated light of stellar populations using CP stars.

- The CP technique has high age resolution compared to the Balmer feature technique because most CP stars turn on or turn off fairly suddenly as a function of population age.
- The CP technique is insensitive to intervening interstellar dust.
- The CP technique avoids the use of Balmer features, and therefore all complications arising from nebular emission.
- The CP technique relies on high S/N galaxy spectra.
- The CP technique also relies on a suitably thorough modeling effort that includes expanded stellar spectral libraries and better empirical constraints on number fractions of CP stars as a function of age, chemistry, and evolutionary state.

Acknowledgements. I would like to thank C. R. Cowley for many stimulating conversations regarding CP stars. I would like especially to thank S. C. Trager for his encouragement and also my esteemed spectral library collaborators P. Coelho, J. Falcón-Barroso, S. R. Heap, A. Lançon, D. Lindler, L. P. Martins, R. F. Peletier, P. Prugniel, P. Sánchez-Blázquez, D. Silva, and A. Vazdekis. The comments of the anonymous referee were very helpful in improving this Letter. Support for program AR-13900 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.

References

Aringer, B., Girardi, L., Nowotny, W., Marigo, P., & Lederer, M. T. 2009, A&A, 503, 913
Bailey, J. D., Landstreet, J. D., & Bagnulo, S. 2014, A&A, 561, A147
Bergeat, J., Knapik, A., & Rutily, B. 2001, A&A, 369, 178
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Conti, P. S. 1991, ApJ, 377, 115
Cowley, A., Cowley, C., Jaschek, M., & Jaschek, C. 1969, AJ, 74, 375
Dobos, L., Csabai, I., Yip, C.-W., et al. 2012, MNRAS, 420, 1217
Fuhrmann, K. 1989a, A&AS, 77, 345
Fuhrmann, K. 1989b, A&AS, 80, 399
Girardi, L., Marigo, P., Bressan, A., & Rosenfield, P. 2013, ApJ, 777, 142
Kramida, A., & Sansonetti, J. E. 2013, ApJS, 205, 14
Landstreet, J. D., Bagnulo, S., Andretta, V., et al. 2007, A&A, 470, 685
Leitherer, C. 2005, in 783, The Evolution of Starbursts, eds. S. Hüttmeister, E. Manthey, D. Bomans, & K. Weis, AIP Conf. Ser., 280
Leitherer, C., Ekström, S., Meynet, G., et al. 2014, ApJS, 212, 14
Levesque, E. M., & Leitherer, C. 2013, ApJ, 779, 170
Marigo, P., Girardi, L., Bressan, A., et al. 2008, A&A, 482, 883
Michaud, G. 1970, ApJ, 160, 641
Michaud, G., Charland, Y., Vauclair, S., & Vauclair, G. 1976, ApJ, 210, 447
North, P. 1993, in IAU Colloq. 138, Peculiar versus Normal Phenomena in A-type and Related Stars, eds. M. M. Dworetsky, F. Castelli, & R. Faraggiana, ASP Conf. Ser., 44, 577
Preston, G. W. 1974, ARA&A, 12, 257
Santos, Jr., J. F. C., & Frogel, J. A. 1997, ApJ, 479, 764
Schaerer, D., Contini, T., & Pindao, M. 1999, A&AS, 136, 35
Smith, K. C. 1996, Ap&SS, 237, 77
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645
Valdes, F., Gupta, R., Rose, J. A., Singh, H. P., & Bell, D. J. 2004, ApJS, 152, 251
Vollmann, K., & Eversberg, T. 2006, Astron. Nachr., 327, 862
Worthey, G. 1994, ApJS, 95, 107
Worthey, G., & Ottaviani, D. L. 1997, ApJS, 111, 377