LOCAL STARBURSTS: PERSPECTIVES FROM THE OPTICAL

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Abstract
The optical regime is historically the best-studied wavelength range. Gas ionized by massive stars produces optical emission lines that have been used to derive indicators of star-formation rate, metallicity, dust reddening, and the ionization conditions of the interstellar medium. Absorptions lines have been used to measure velocity dispersions, and the 4000 Å break has been shown to be a useful indicator of the mean age of stellar populations. I briefly summarize some recent work done on, specifically, star formation rate indicators, in view of their importance for understanding star-forming galaxies at high redshift.

Keywords: galaxies: starbursts; star formation rates; dust: extinction

1. Introduction

In recent years, the advent of improved infrared instrumentation on large, 8–10 m class, telescopes has opened a window on rest-frame optical observations of high redshift galaxies, and revived interest for this historically well-studied wavelength regime.

The easy access from the ground to the optical emission from local celestial bodies (stars, HII regions, galaxies, etc.) has led to the development and definition of a series of tracers of the physical and chemical conditions of these objects. Of immediate relevance for complex systems like galaxies are the nebular emission lines, stellar and interstellar absorption lines, and broad-band features like the 4000 Å break.

The 4000 Å break, for instance, is an estimator of a stellar population’s mean age (e.g., Kauffmann et al. 2003), while absorption lines have been widely employed to measure velocity dispersions within the stellar systems. Among all optical tracers of physical and chemical conditions, however, the lion’s share goes to the nebular emission lines. The gas ionized by young, massive stars produces optical emission lines from a number of chemical elements, and with a fairly large range of intensities; these have been ‘calibrated’ to ‘measure’:
star formation rates (SFR; from [OII], Hα, ...);

gas chemical abundances (O, N, S, ...);

dust reddening (e.g., from the Balmer series);

diagnostics of star–formation feedback, and, in general, ionization conditions ([OI], [NII], [SII], ...).

The applicability of any such indicator for investigations at cosmological distances depends on the redshift range under consideration, and the number of lines that can be accessed. The [OII](λ3727 A) emission line is sufficiently blue to be observable in the optical window up to redshift less or about 1.5; however, this line alone (with no other information at shorter or longer wavelengths) can only provide a highly uncertain estimate of the distant galaxies’ SFRs (see next section, and, e.g., Hammer et al. 1997, Hogg et al. 1998, Rosa–Gonzalez et al. 2002, Hippelein et al. 2003, Teplitz et al. 2003, Kewley et al. 2004). New infrared instruments are providing more leverage, by allowing investigators to access a larger suite of restframe optical emission lines, from [OII](λ3727 A) to [NII](λ6584 A), up to, for some lines, redshift $z \sim 3$. Multiple emission lines from the same cosmological object afford better estimates of dust reddening, gas chemical abundances, etc. (e.g., Teplitz et al. 2000, Pettini et al. 2001, Lemoine–Busserolle et al. 2003). Last, but not least, once the James Webb Space Telescope is on orbit, from its vantage point above the atmosphere it will provide an unobstructed view of the earliest galaxies, detecting Hα up to $z \approx 6.5$, and, potentially, as high as $z \approx 40$ (depending on sensitivity and whether ionizing objects exist at such high redshifts). Redshift $z=6.5$ corresponds to an epoch when the Universe was 6% of its current age (for a ΛCDM cosmology).

Given that the high–redshift ‘frontier’ employs tools derived from the more accessible low–redshift Universe to understand the evolution of galaxies, it is worth revisiting the strengths and limitations of some of these tools, and whether more investigation is needed in some areas. For instance, recent studies have re-iterated the limitations of the well–known and well–established ‘strong line method’ for chemical abundance measurements in metal–rich environments (Garnett et al. 2004).

In this talk I concentrate on the SFR indicators accessible in the optical regime, highlighting recent progress in the area; I connect these optical indicators to those at other wavelengths, suggesting where additional investigation may be needed.
2. Star Formation Rate Indicators in the Optical

The basic questions that come to mind when using SFR indicators at optical or other wavelengths are: are they consistent with one another? What level of ‘uncertainty’ each of them carries, and what factors produce such uncertainty?

At optical wavelengths, the two most widely employed SFR tracers are: the Balmer lines emission ($H\alpha$, $H\beta$, ...) and the [OII]($\lambda 3727$ Å) doublet line emission. Both are measures of ‘instantaneous’ star formation, as the gas is excited by the ionizing photons of the short–lived O and early–B stars. The intensity of both Balmer and [OII] lines is affected by dust extinction – the $H\alpha$ less than the bluer $H\beta$ and [OII] –, and by changes in the upper end mass of the stellar Initial Mass function (IMF, which affects the number of ionizing photons available to excite the gas). The intensity of the Balmer lines is additionally affected by the stellar absorption of the underlying galaxy stellar population – again the $H\alpha$ at a lower level than $H\beta$. In contrast, the [OII] is affected by the gas metallicity and, potentially, by its ionization conditions (but, see, Kewley et al. 2004, who find no such influence for galaxies with O/H > 8.5). A non–exhaustive list of studies addressing such effects and/or deriving calibrations for SFR estimates from line measurements includes: Gallagher et al. 1989, Kennicutt 1992, 1998, Charlot et al. 2002, Rosa–Gonzales et al. 2002, Kewley et al. 2002, 2004, Perez–Gonzalez et al. 2003, Hopkins 2004.

Combined, the above effects impact SFR estimates from factors of a few to orders of magnitude, depending on the regime where the measurement is performed. This is easily seen in the case of dust extinction. Local starburst galaxies cover a wide range of dust attenuation values; even UV–selected starbursts can show extinctions as high as $A_V \sim 4.5$ mag, with a loose trend for more actively star–forming galaxies to have higher extinctions (Figure 1, left; see, also, Wang & Heckman 1996, Sullivan et al. 2001, Perez–Gonzalez et al. 2003). If such a highly extincted galaxy is mistakenly corrected for a lower extinction value, e.g., $A_V \sim 1$ mag (the value derived for disks, Kennicutt 1983), the derived SFR($H\alpha$) will underestimate the actual one by a factor of 14!

How common are such galaxies? From the $H\alpha$ luminosity function of Perez–Gonzalez et al. (2003), an $L^*(H\alpha)$ galaxy in the local Universe has $A_V^* \approx 2–3$ mag, thus galaxies with heavily extincted ionized gas are not a rarity in our cosmological neighbourhood. How this translates to higher redshifts is still unclear, although there are suggestions that overall extinctions are decreasing at constant SFR in high-redshift galaxy populations (Adelgerber & Steidel 2000).

The SFR–extinction correlation carries down to the ‘quiescent’ star-forming galaxy regime, with a trend that is resemblant of the starburst galaxies’ one (Figure 1, right). The fact that more actively star–forming galaxies and regions have, on average, larger dust extinction values is a consequence of the Schmidt–
Figure 1.  (Left) The dust attenuation at V for the ionized gas, A_V, versus SFR for the starburst galaxies sample of Calzetti et al. (1994). The SFR is calculated from the extinction–corrected Hα, while A_V is derived from various hydrogen emission lines, from Hβ in the optical to Brγ in the infrared. The continuous line is the best linear fit through the datapoints. (Right) The A_V versus SFR for HII-emitting complexes in the central ~6 kpc of M51a (Calzetti et al. 2005). A_V is derived from the Hα/Pα line ratio, and SFR is calculated from the extinction–corrected Pα(λ1.8756 μm). The continuous line is the best fit through the points, while the dotted line is the starburst galaxies fit (left panel), vertically rescaled by a factor $10^{3.35}$.

Kennicutt law (galaxies/regions with larger gas surface densities show larger specific SFRs, e.g., Kennicutt 1998) combined with the mass–metallicity relation (see, also, Tim Heckman’s contribution to this conference).

Measurements of the stellar IMF are ridden with controversy (see review by Brandl & Andersen 2004). Amid all this, the high-end of the stellar IMF appears to be fairly constant from galaxy to galaxy in the local Universe, and, possibly, has not changed from the high redshift to the present day (Stasinska & Leitherer 1996; Wyse et al. 2002; Elmegreen, this Conference). If variations do exist, they are likely a second–order effect at least for what concerns SFR measurements. The comparison between SFR(IR) and SFR(Hα) for a sample of local galaxies by Kewley et al. (2002) supports such statement. SFR(IR) is the star formation calculated from the galaxies’ far–infrared emission, which is due to dust heated mainly by the stellar non–ionizing radiation (UV, optical, etc.). Thus, two different aspects of the stellar bolometric luminosity, the non–ionizing and the ionizing ones, determine SFR(IR) and SFR(Hα), respectively. The tight agreement between SFR(IR) and SFR(Hα), within ~10%, over 4 orders of magnitude (Kewley et al. 2002) is supportive of a relatively constant upper-end of the IMF.

The impact of the underlying stellar absorption can be quite significant on the Balmer emission lines, for two reasons: 1) since EW_{abs}(Hα)≈EW_{abs}(Hβ), the intrinsically weaker Hβ line emission will be proportionally more ‘depressed’ by the underlying absorption than the Hα, altering measurements of
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dust reddening; 2) in galaxies where the star formation intensity is proportionally a small fraction of the overall stellar emission, the $EW_{abs}(H\alpha)$ can be a significant fraction of the $EW_{em}(H\alpha)$, thus leading to underestimates of the emission fluxes. Measurements of local star–forming galaxy populations indicate values of $EW_{abs}(H\alpha)\sim$3–6 Å (Kennicutt 1992, Calzetti et al. 1994, Charlot et al. 2002, Rosa-Gonzalez et al. 2002), with the smaller value more commonly applicable to starburst galaxies.

These studies demonstrate that once the effects of dust extinction and underlying stellar absorption are controlled, the $H\alpha$ emission is a reliable indicator of instantaneous SFR, and existing calibrations (Kennicutt 1998) are sufficiently accurate for most purposes. For SFR([OII]), there are additional effects to consider: the dependence on metallicity and, potentially, on the ionization conditions, but these can be ‘calibrated’ in samples of local galaxies (Kewley et al. 2004) or empirical approaches can be adopted (Kennicutt 1998, Rosa-Gonzales et al. 2002). Problems arise when only a limited amount of information, e.g., just one or two adjacent emission lines, is available, as often is the case for samples at cosmological distances. In these cases, the unknown dust extinction and underlying stellar absorption corrections can lead to two effects: 1) underestimates of the actual SFRs by a factor of a few, up to an order of magnitude, depending on the nature of the sample and the restframe wavelength region investigated; 2) increase in the dispersion of the SFR distribution of the sample by at least a factor of 2 (Rosa–Gonzales et al. 2002).

3. Star Formation Rate Indicators at Other Wavelengths

The optical SFR indicators discussed above measure the presence and amount of ionizing stars in galaxies, which are typically short–lived ($t_{life} < 10^7$ yr). Some of the other widely used SFR indicators at shorter or longer wavelengths probe star formation over longer timescales, typically 100 Myr or longer.

This is the case, for instance, of the restframe UV emission (where UV is intended here as the stellar emission between 1000 Å and 3000 Å). While the UV emission is well correlated with the ionized line emission in starburst galaxies (and thus both represent reliable tracers of current SFR), there is increasing evidence that the UV of quiescent star–forming galaxies traces recent, but not current, star formation, and cannot be directly used as an ‘instantaneous’ SFR indicator (Kong et al. 2004, Calzetti et al. 2005).

Another popular SFR indicator is the one derived from a galaxy’s far infrared emission, SFR(IR). As mentioned in the previous section, the far infrared emission in a galaxy is from dust heated mainly by the non–ionizing stellar radiation. One of the standing questions is how much of the IR radiation from a galaxy is contributed by current or recent star formation, and how
much by the general stellar radiation field. The answer to this question can affect the empirical calibration of SFR(IR).

Addressing some of those questions is one of the purposes of projects like SINGS (the Spitzer Infrared Galaxies Survey, one of the Spitzer Legacy Projects; P.I.: R. Kennicutt; see J.D. Smith’s contribution to this conference). The unprecedented angular resolution afforded by Spitzer together with observations at multiple wavelengths of local galaxies is enabling this project to shed light on the merits and problems of common (and uncommon) SFR indicators, for use on galaxies at cosmological distances.

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