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Multiwavelength Diagnostics of Star Formation Rates

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Abstract.
An important science goal of the SINGS project is to develop hybrid extinction-corrected star formation rate (SFR) indices, based on the combination of infrared with optical and/or ultraviolet SFR tracers. these can provide the most robust extinction-free estimates of SFRs We present preliminary results from two studies that use the combination of Hα and the 24 μm luminosities of galaxies to derive extinction-corrected ionizing fluxes and SFRs for HII regions and galaxies, respectively. These have been applied to measure the form of the spatially-resolved SFR vs gas density Schmidt law in M51.

1. Introduction

One of the longstanding limitations in measuring star formation rates (SFRs) in galaxies is the difficulty in adequately correcting for the effects of variable dust obscuration. On average dust absorbs roughly half of the emergent luminosity of a star-forming galaxy in Hα and the ultraviolet, but this attenuation[1] varies enormously within and among galaxies, ranging from less than 10% in many dwarf galaxies to >99% in the circumnuclear regions of many infrared-luminous galaxies. Correcting for this attenuation using optical, ultraviolet, or infrared observations alone is problematic. Integrated reddenings measured from the UV continuum or nebular emission lines provide reliable attenuation corrections for individual OB/HII regions, and have been applied with some success to galaxies as a whole (e.g., Calzetti 2001, Kewley et al. 2002, Brinchmann et al. 2004). But these require multi-wavelength observations or integrated spectrophotometry of the galaxies, and this is not always available. These corrections are also subject to systematic errors introduced by the variable extinction within galaxies (see Calzetti 2001 and references therein). In very dusty galaxies the integrated infrared luminosity can provide a more reliable SFR measure, but the conversion from IR luminosity to SFR is also sensitive to the opacity of the galaxy and the age mix of the stars heating the dust (Kennicutt 1998a and references therein).

[1]Throughout this paper we will adopt the convention of using the term "attenuation" to refer to the net reduction in flux received from an HII region or galaxy at a particular wavelength, taking into account the combined effects of dust extinction and scattering.

Hence is it hardly surprising that uncertainties in dust corrections are the largest source of systematic error in our current measurements of SFRs.

The thermal infrared emission of a star-forming region or galaxy represents the energy removed by the dust in the UV and visible, so it should be possible in principle to recover the attenuation correction by combining flux measurements in the two wavelength regimes. Gordon et al. (2000) introduced this approach as the "flux ratio method" and applied it to derive attenuated-corrected UV luminosities and SFRs of starburst galaxies. We have been exploring the the possibility of combining the observed Hα and infrared fluxes of HII regions and galaxies to derive attenuation-corrected Hα luminosities and SFRs. These provide much more robust attenuation corrections than most other current methods, and they offer great promise for providing extinction-corrected SFRs for large samples of galaxies, across the full range of extinctions, and as a foundation for testing other SFR methods for when multi-wavelength data are not available.

2. Basic Method

An early surprise of the SINGS project was the degree of spatial correlation between the discrete infrared sources observed in galaxies in the MIPS 24 μm images and in Hα emission-line images, as is illustrated in Figure 1 for M81. Given that dust absorbs roughly half of the integrated Hα emission of a galaxy, one might expect to observe a large population of deeply embedded clusters and compact HII regions. To our surprise fewer than 4% of the 24 μm sources in luminous spiral galaxies have $A_V \geq 5$ mag, and most *infrared-selected* sources have attenuations in the range 0–3 mag (Prescott et al., this volume).

The tightness of this association has been quantified in studies of M51 and M81 by Calzetti et al. (2005) and Pérez-González et al. (2006), respectively. Calzetti et al. observed a very tight and linear correlation between 24 μm fluxes and the extinction-corrrected Pα fluxes of HII regions in the dusty inner disk of M51, and in M81, where the attenuations are lower, we found that the 24 μm fluxes are well correlated with the *extincted component* of the nebular ionizing fluxes (i.e., the Hα emission attentuated by dust, as inferred from independent extinction measurements from the radio and from Balmer decrement measurements). The correlations appear to be tightest at 24 μm, at least for HII regions, and become less tight at shorter and longer wavelengths, mainly because the colder dust emission and the PAH emission have larger components arising from heating by "older" stellar populations (i.e., non-ionizing populations).

This tight association between the 24 μm emission of HII regions and the extincted components of their ionizing fluxes suggests that we can apply a variant of the Gordon et al. flux ratio method to the Hα measurements, using the observed 24 μm/Hα flux ratios to correct the Hα fluxes for extinction. We can express the corrected Hα luminosity as a weighted sum of the observed Hα and 24 μm luminosities:

$$L(H\alpha)_{corr} = \alpha \ L(24) + L(H\alpha)_{obs} \qquad (1)$$

The scaling constant α is derived emprically, using an independent extinction-corrected total SFR measure such as (in the case of M51) the Pα luminosity. We should not expect the same scaling constant to apply for HII regions, more

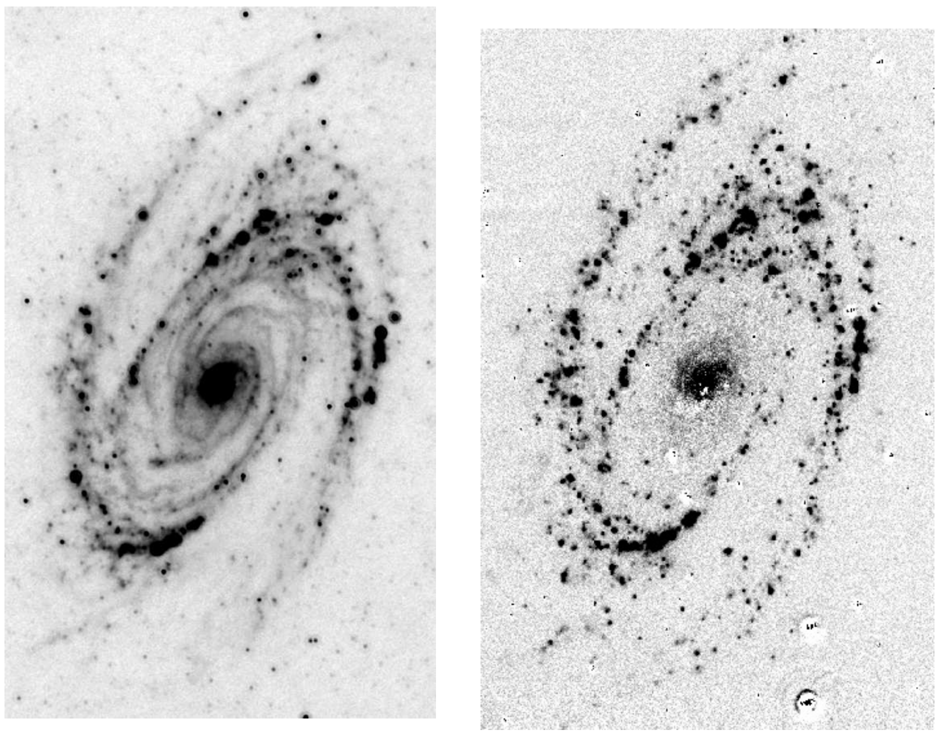

Figure 1. The nearby SINGS Sb galaxy M81 (NGC 3031) observed at 24 μm (left), and at Hα (right), showing the close correspondence between the bright infrared sources and optical HII regions.

extended starbursts, and galaxies as a whole, because of the differences in stellar age components that dominate their infrared continuum emission.

This method is an approximate empirical correction at best, because it does not take into account complicating factors such as scattering, the geometry of gas and dust, and contributions to the extinction and the 24 μm emission from foreground and background regions. It also assumes a similar 24 μm to FIR SED for all regions. We know that these simplifications break down in detail, so the utility of the method is limited by its assumptions, and its accuracy must be determined empirically. Nevertheless, we shall see that the method provides surprisingly reliable corrections so long as one avoids situations where it clearly must break down (e.g., edge-on galaxies, small HII regions dominated by ionization of a single star, etc.).

3. Application to HII Regions in M51

Our first attempt to calibrate and apply this method was for M51, where we have 42 HII regions in the inner disk with reliable Pα, Hα, and 24 μm flux measurements (Calzetti et al. 2005). The Pα fluxes were corrected for extinction using the Pα/Hα ratio (because Pα has a wavelength of 1.87 μm these extinction corrections are small, usually $\leq$0.4 mag). We then combined the 24 μm and Hα

fluxes to derive equivalent extinction-corrected Pα fluxes using eq. (1) and a intrinsic Pα/Hα ratio of 8.734. We fitted the scaling constant α in eq. (1) by requiring that the median flux scale agree with that derived from the extinction-corrected Pα data. This yields a value $\alpha = 0.049 \pm 0.005$.

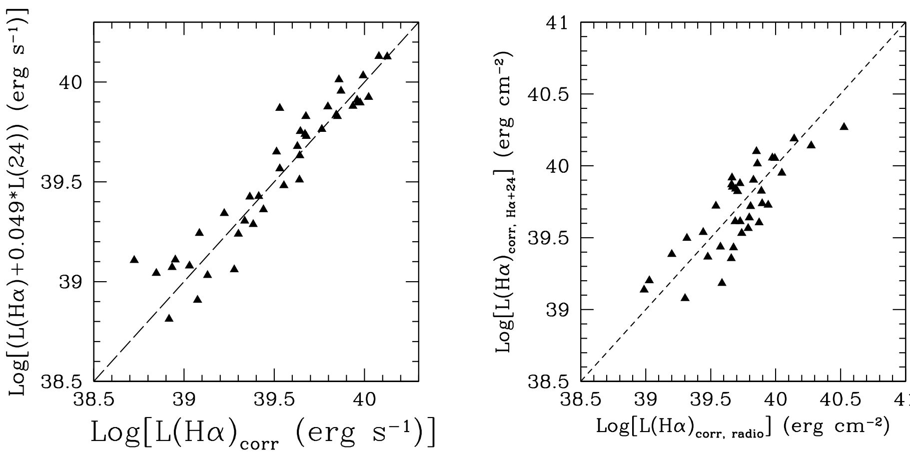

Figure 2. Comparison of extinction-corrected Hα fluxes for HII regions in M51 using the combination of Hα and 24 μm fluxes (eq. [1]), with equivalent fluxes derived independently from extinction-corrected Pα fluxes (left) and thermal radio continuum fluxes (right).

The consistency of these extinction-corrected luminosities is shown by the low scatter of points about the fit in the left panel of Figure 2. In the righthand panel we compare the corrected luminosities to those derived from the radio continuum measurements of van der Hulst et al. (1988). This provides a completely independent test, and the scatter is consistent with the estimated uncertainties in the radio measurements alone.

As an early application of this method we used the observed Hα and 24 μm luminosities of 258 HII regions in M51 to derive extinction-corrected ionizing fluxes, and we correlated these in turn with high-resolution HI and CO maps to study the form of the SFR vs gas density Schmidt law on a point-by-point basis in the galaxy (Kennicutt et al. 2006, in preparation). The results are shown in Figure 3. The data trace a Schmidt power law with slope $N = 1.57 \pm 0.04$ (statistical errors only). When we repeat the experiment averaging over $45''$ (1850 pc) apertures the slope changes slightly, to $N = 1.38 \pm 0.03$ (again statistical uncertainties only). These relations are very similar to the slope $N = 1.4 \pm 0.1$ that is observed in the disk-averaged SFRs and gas densities in galaxies (Kennicutt 1998b), and are probably the same within the errors when systematic uncertainties such as variations in the CO/H_2 conversion factor are taken into consideration (Kennicutt et al. 2006).

4. Application to the Integrated SFRs of Galaxies

The same method should provide comparably robust extinction-corrected SFRs of galaxies as a whole. However we should expect the scaling constant between

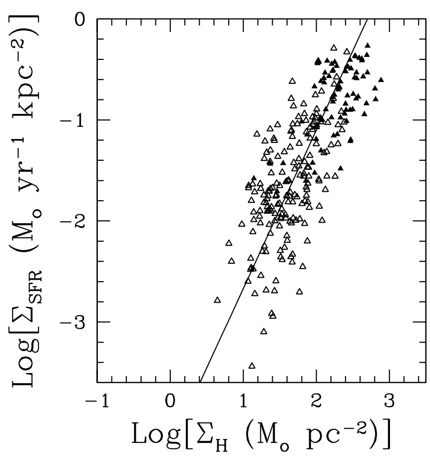

Figure 3. Correlation of SFR density and total (atomic + molecular) gas density for 258 regions in M51, with aperture sizes of 520 pc.

24 μm and Hα fluxes to be different, because whereas in HII regions the bulk of the ionization and dust heating both arise from very young stars (ages 0–10 Myr), in more extended starbursts or in normal galaxies stars older than 10 Myr will contribute significantly to the infrared emission (but add neglibly to the ionizing fluxes). Our group is pursuing this approach on two fronts. We have extended the study of Pα measurements to a large sample of SINGS galaxies observed with HST, as described in a separate paper in this volume by Calzetti (also see Alonso-Herrero et al. 2006). Independently I have been working with the integrated measurements of the SINGS galaxies (Dale et al. 2005) and with a large sample of galaxies with integrated optical spectra (Moustakas & Kennicutt 2006; hereafter MK06) and IRAS measurements to calibrate and test integrated SFRs measured in this way.

Preliminary results from this latter study are shown in Figure 4. The left panel shows integrated SFRs estimated from the 25 μm IRAS luminosity alone (Y-axis) and the reddening-corrected Hα luminosities from MK06 (X-axis). We restricted this comparison to galaxies which had better than 3σ IRAS detections at 25 μm reliable absorption-corrected Hα/Hβ reddening measurements, and had integrated spectra indicating dominant ionization by star formation (i.e., strong AGNs were excluded). The SFRs are based on the calibrations published in Kennicutt (1998a), with the far-infrared calibration roughly converted to 25 μm using the average 25/FIR ratio of the sample, strictly for comparative purposes. The SFRs show a reasonable correlation, as first pointed out by Kewley et al. (2002). But there is clearly a significant scatter and a nonlinear trend, which is mainly caused by a systematic increase in extinction with galaxy luminosity (which here is reflected statistically in the absolute SFR).

In the righthand panel use the combination of observed Hα and 25 μm luminosities and eq. (1) to estimate SFRs. In this case a scaling constant α of 0.022 was used; this includes a factor of 1.14 to adjust the IRAS 25 μm flux scale to the MIPS 24 μm scale (as derived from the Dale et al. data), and a factor of 2 as my *guess* of what the correction for dust heating by stars outside

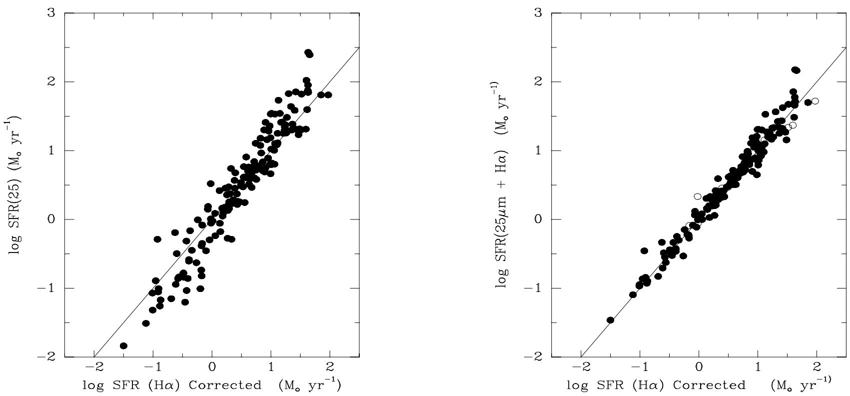

Figure 4. (Left) Comparison of integrated SFRs derived from integrated IRAS 25 μm luminosities and reddening-corrected Hα luminosities, for a sample of star-forming galaxies in the spectral atlas sample of Moustakas & Kennicutt (2006). (Right) Comparison of SFRs derived from eq. (1) with reddening-corrected Hα luminosities for the same sample. See text for details.

the HII regions would be. Remarkably, the corrected Hα + 25 μm SFRs show an excellent agreement with the reddening-corrected Hα-derived SFRs, despite my guess at the scaling factor. Using the FIR luminosity in place of the 25 μm luminosities produces an even tighter relation, at least for this sample. We refer the reader to Kennicutt & Moustakas (2006, in preparation) for details.

Clearly these are but preliminary results and need to be followed up with more extensive datasets. Apart from refining the results presented here and in Calzetti et al. (this volume) we will be using the complete multi-wavelength coverage of the SINGS galaxies themselves to test and refine a variety of multi-wavelength SFR indicators, as global and local SFR tracers.

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References

Alonso-Herrero, A. et al. 2006, submitted to ApJ
Brinchmann, J. et al. 2004, MNRAS, 351, 1151
Calzetti, D. 2001, NewAR, 45, 601
Calzetti, D. et al. 2005, ApJ, 633, 871
Dale, D.A. et al. 2005, ApJ, 633, 857
Gordon, K.D. et al. 2000, ApJ, 533, 236
Kennicutt, R.C. 1998a, ARA&A, 36, 189
Kennicutt, R.C. 1998b, ApJ, 498, 541
Kewley, L. et al. 2002, AJ, 124, 3135
Moustakas, J., & Kennicutt, R.C. 2006, ApJS, in press, astro-ph/0511725
Pérez-González, P. et al. 2006, submitted to ApJ
van der Hulst, J.M. et al. 1988, A&A, 195, 38