Optical spectroscopy of Arp220: the star formation history of the closest ULIRG

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ABSTRACT
We present long-slit, optical spectra of the merging system Arp 220, taken with the William Herschel Telescope (WHT) on La Palma. These data were taken as a part of a large study of ultraluminous infrared galaxies (ULIRGs) with the aim of investigating the evolution and star formation histories of such objects. Spectral synthesis modelling has been used to estimate the ages of the stellar populations found in the diffuse light sampled by the spectra. As the closest ULIRG, it proved possible to perform a detailed study of the stellar populations over the entire body of the object. The data show a remarkable uniformity in the stellar populations across the full 65 arcsec covered by our slit positions, sampling the measurable extent of the galaxy. The results are consistent with a dominant intermediate-age stellar population (ISP) with age $0.5 < t_{ISP} \leq 0.9$ Gyr that is present at all locations, with varying contributions from a young ($\leq 0.1$ Gyr) stellar population (YSP) component. However, it is notable that while the flux contribution of the YSP component in the extended regions is relatively small ($\leq 40\%$), adequate fits in the nuclear region are only found for combinations with a significant contribution of a YSP component (22 - 63\%). Moreover, while a low intrinsic reddening ($E(B-V) \lesssim 0.3$) is found for the ISPs in the extended regions, intrinsic reddening values as high as $E(B-V) \sim 1.0$ are required in the galactic center. This clearly reflects the presence of a reddening gradient, with higher concentrations of gas and dust towards the nuclear regions, coinciding with dust lanes in the HST images. Overall, our results are consistent with models that predict an epoch of enhanced star formation coinciding with the first pass of the merging nuclei (represented by the ISP), with a further episode of star formation occurring as the nuclei finally merge together (represented by the YSP and ULIRG).

1 INTRODUCTION
Since the early 1980s, several studies have revealed the presence of galaxies with the spectral energy distribution dominated by infrared emission (Houck & et al., 1984; Houck et al., 1985; Soifer & et al., 1984a,b; Soifer et al., 1987; Le Floc’h et al., 2005). These galaxies are classified as Luminous ($L_{IR} > 10^{11} L_{\odot}$) or Ultraluminous ($L_{IR} > 10^{12} L_{\odot}$) infrared galaxies (LIRGs/ULIRGs). Their prodigious infrared emission is generally attributed to the optical/UV light of luminous central sources reprocessed by dust. Starburst activity is ongoing in most, if not all, of these sources, coexisting with AGN activity in some cases (Genzel et al., 1993; Surace & Sanders, 1999; Veilleux et al., 1999). Therefore these objects provide us with an excellent opportunity to study both AGN and starburst phenomena. Moreover ULIRGs are almost invariably associated with galaxy mergers and interactions (see Sanders & Mirabel (1996) for a revision). Thus, they also represent ideal objects to test models of galaxy evolution via major galaxy mergers. (e.g. Mihos & Hernquist, 1996; Barnes & Hernquist, 1996; Springel et al., 2005.)

In this context Arp220, as the closest ULIRG ($z = 0.018$), is a key object for our understanding of starformation in galaxy mergers. At infrared wavelengths, it appears as a double nucleus system (Graham et al., 1990; Scoville et al., 1998) separated 0.95 arcsec, with two tidal tails visible at optical wavelengths (Joseph & Wright, 1985). Although the mid-IR spectra suggest starburst activity as the main source of power for the infrared continuum (Genzel et al., 1998; Lutz et al., 1999), the galaxy is classified as a LINER in the optical (Veilleux et al., 1999). Arp

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26 was also observed by Scoville et al. (1997) at 1.3 and 2.6 \( \mu m \) emission. They determine a total \( H_2 \) mass of \( 3.2 \times 10^{10} M_\odot \), of which 2/3 is contained within 250 pc and confined to a thin, centrally located, dense disk, embedded in a CO disk extended by \( \sim 1 \) Kpc. The dynamics of the nuclear region are consistent with a collision between prograde and retrograde disks overlapping with the main gas disk (Mundel et al. 2001, see figure 7 in their paper). Recently, Wilson et al. (2006) performed a detailed photometric study of the star clusters in Arp220. They found evidence that the cluster population can be divided into two groups: a centrally located young population of age \( t_{\text{YSF}} < \leq 10 \) Myr, and an intermediate-age population of age \( \sim 300 \) Myr spread towards the north of the galaxy. However, given the photometric uncertainties, it is not straightforward to break the age/reddening degeneracy problem unambiguously in such studies, based only on colour-colour diagrams with relatively few filters.

To date, there have been few spectroscopic studies of stellar populations in ULIRGs. To remedy this situation we present in this paper a detailed study of the stellar populations in Arp220, based on spectroscopic observations of the extended diffuse light along three slit positions. The results are discussed in the context of evolutionary models of star formation in mergers.

Throughout the paper we assume \( H_0 = 71 \) km \( s^{-1} \), \( \Omega_0 = 0.27 \) and \( \Omega_\Lambda = 0.73 \), resulting in a scale of 0.363 kpc arcsec\(^{-1} \) and a distance of 77.6 Mpc at \( z = 0.018 \).

## 2 OBSERVATIONS AND DATA REDUCTION

Spectra of Arp220 were taken in July 2005 and 2006 with the ISIS dual-beam spectrograph on the 4.2-m William Herschel Telescope (WHT) on La Palma. The R300B grating with the EEV12 CCD, and R316R grating with MARCONI2 CCD were used on the blue and the red arms respectively. A dichroic cutting at 5300Å was used during the observations, leading to a useful wavelength range in the rest frame of 3000 – 5000Å in the blue, and 5000 – 7800Å in the red. The spectra were taken along three slits positions: PA 160, PA 75 and PA 75* (10 arcsec offset to the north of PA 75), covering the nuclear region and also the tidal tail observed towards the North-West of the galaxy. Details of the observations are given in Table 1. Figure 1 shows the slit positions superimposed on HST images taken with the WFPC2 (HST proposal 6346, PI K.Borne) and the ACS HRC (HST proposal 9396, PI C.Wilson) camera. To find the precise locations of the slits on the images we first convolved the images with Gaussian profiles to simulate the seeing conditions during our WHT observations. Several spatial profiles were then extracted from the images and compared with those of spatial slices extracted from the spectra using a wavelength range as close as possible to that of the images, until a match was found. All exposures were taken with the slit aligned along the parallactic angle, in order to minimize the effects of the differential refraction.

The data were reduced (bias subtraction, flat field correction, cosmic ray removal, wavelength calibration and flux calibration) and straightened before the extraction of the individual spectra using the standard packages in \textit{IRAF} and the \textit{STARLINK} packages \textit{FIGARO} and \textit{DIPSO}. The wavelength calibration accuracy, calculated as the mean value of the difference between the published (Osterbrock et al., 1996) and the actual wavelengths of the night sky lines was estimated as \( < 0.34 \)Å and \( < 0.45 \)Å in the blue and the red respectively. The spectral resolution, calculated as the mean value of the sky line width (FWHM) was 5.80Å in the blue and 5.25Å in the red. The relative flux calibration accuracy, based on the observation of several spectrophotometric standard stars, is estimated as \( \pm 5\% \) over the entire range.
Figure 2. The Balmer break ratio $R_B$ plotted as a function of position along PA 160. The small variations of the ratio suggest a remarkable uniformity for the stellar populations along the extension covered by the slit position. The centroid of Ap D is used as the reference point. Positive x = North, Negative x = South.

spectral range. This is confirmed by the excellent match between the blue and the red spectra for all the apertures extracted. Prior to the modelling, the spectra were corrected for Galactic extinction using the Seaton (1979) reddening law and the value of $E(B-V) = 0.051$ from Schlegel et al. (1998).

3 RESULTS

In order to gain a preliminary impression of the variations of the stellar populations, in Figure 2 we plot the flux ratio:

$$R_B = \frac{\int_{4080}^{4000} F_\lambda d\lambda}{\int_{3700}^{3620} F_\lambda d\lambda}$$

as a function of position along PA 160. This ratio, which is designed to provide a sensitive measure of the Balmer break, shows remarkably little variation across the galaxy (typical variation ± 10%) except in the region of the nucleus (within ± 5" of the center) which is subject to enhanced reddening.

To further investigate the stellar populations, 20 apertures were extracted along the three slits positions with the aim of adequately sampling the different regions observed in both the 2-D spectra and the available HST images. These apertures are labelled in Figure 1. Three larger apertures, including all the small apertures for each slit PA, were also extracted, the latter are labelled as $A_{P A}^L$ in Fig 3 and Table 2 and 3. The apertures extracted for the three slit positions are shown superimposed on spatial profiles of the 2-D spectra in Figure 3. The apertures were chosen to be wide enough to have a sufficiently high S/N ratio for further analysis: S/N > 15. We would like to emphasize that the S/N is considerably higher than this for most of the apertures extracted from the different regions of the galaxy. A sample of extracted spectra is shown in Figure 4. The strong Balmer lines and Balmer break present across the full measurable extent of the galaxy (65 arcsec) indicate that young and/or intermediate age stellar populations are present in all spatial apertures. The overall SEDs also show signs of enhanced reddening in the nuclear regions (apertures D and E, PA 160).

In order to obtain a more detailed information about the stellar populations we have modelled the spectra extracted from the apertures using the evolutionary synthesis models of González Delgado et al. (2005) and Bruzual & Charlot (2003). These models incorporate high and intermediate spectral resolution stellar libraries. Such resolutions are required to isolate the nebular and the stellar absorption contributions in the spectra of this type of galaxies. To generate
these templates we have assumed a Salpeter (1955) initial mass function, instantaneous starburst and solar metallicity (see Tadhunter et al., 2005, for a justification of these assumption). We then reddened the synthetic spectra using both the Calzetti et al. (2000) reddening law, appropriate for starburst galaxies, and the Seaton (1979) reddening law, representing the Galactic extinction case. Overall, there is good consistency between results obtained with the two reddening laws, demonstrating that the main results are not sensitive to the details of the reddening law assumed, at optical wavelengths.

To determine the detailed properties of the young stellar populations we have to fit the whole observed spectrum. We have used two different approaches to perform the fit and determine the best models results. They involve STARLIGHT (Cid Fernandes et al., 2005) and CONFIT (Robinson et al., 2000; Tadhunter et al., 2005; Rodríguez Zaurín et al., 2007; Holt et al., 2007) codes. The former allows up to 11 stellar components but with the same extinction for all components. On the other hand, the CONFIT approach assumes only two stellar population components of different age, but allows these components to have different reddening. More details of the two techniques are given in sections 3.1 and 3.2.

Throughout this paper, we define young stellar populations (YSPs) as stellar components with ages $t_{\text{YSP}} \leq 0.1$ Gyr, intermediate-age stellar populations (ISPs) as stellar components with ages in the range of $0.1 < t_{\text{ISP}} \leq 2$ Gyr and old stellar populations (OSP) as a SSP with age 12.5 Gyr. Note that we have not used stellar populations with ages in the range of 2 Gyr $< t_{\text{ISP}} < 12.5$ Gyr. Generally, for models that include young and intermediate/old stellar populations, which is the case for both CONFIT (2 stellar components plus a power law in some cases) and STARLIGHT (11 stellar components), it is not possible to distinguish between ages within this range, and therefore we decided not to use such stellar populations during the modelling analysis described below.

### 3.1 Results from STARLIGHT

STARLIGHT fits simultaneously the continuum points and the absorption lines (high order Balmer lines, He lines, CaII H, CaII K, G-band...). The program reads an input file that labels the spectral windows that contain emission lines, and these spectral ranges are excluded of the fitting. In these models, we have only used the SSP from the evolutionary models. The intrinsic extinction is modelled by a foreground dust screen, and parametrized by the V-band extinction, $A_V$. The output is the population vector that represents the fractional contribution of each SSP of a given age and metallicity to the model flux at a given wavelength. The fit is carried out with a simulated annealing plus Metropolis scheme (Cid Fernandes et al., 2005), which searches for the minimum chi-squared between the observations and the combined models.

For this work we used 11 SSP, corresponding to ages 4, 5, 10, 25, 40, 100, 280, 500, 890 Myr, and 1.25 and 14 Gyr from models by González Delgado et al. (2005). We use solar metallicity, and the Calzetti et al. (2000) extinction law. The results obtained are shown in Table 2 and are summarized as follows:

- OSP contribute very little to the optical continuum. Only a few percent of the flux at 4020 Å is due to stellar populations older than 2 Gyr.
- ISPs with ages in the range of 0.5 Gyr $< t_{\text{ISP}} < 0.9$ Gyr account for $\sim 70\%$ of the optical continuum in all apertures apart from apertures D and E in PA 160, sampling the nucleus of the galaxy.
- The contribution of YSP ($\leq 100$ Myr) is significant $(\geq 30\%)$ in the nuclear regions.
- While low intrinsic reddening is found in the extended regions (0.0 $\leq E(B-V) \leq 0.4$ ), large intrinsic reddening, $E(B-V) \sim 0.7 – 0.8$ is required towards the centre of the galaxy.
- The modelling results found for the three large apertures are consistent with those of the smaller ones and with each other, as shown in the table.

### 3.2 Results from CONFIT

The CONFIT approach consists of a direct fit of the overall continuum shape of the extracted spectra us-

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Noting on a minimum $\chi^2$ technique (Tadhunter et al., 2003; Rodríguez Zaurín et al., 2007). CONFIT is based on a “simplest model” approach, i.e. we fit the minimum number of stellar components required to adequately model the data. The main advantage of this approach is that it allows a wide range of reddening values for each of the components to be explored. For this work we have used different combinations of two stellar components (ISP + YSP) with a range of reddening for each component. For each spectroscopic aperture the continuum flux was measured in several wavelength bins ($\sim 70$) chosen to be as evenly distributed in wavelength as possible, and to avoid strong emission lines and atmospheric absorption features. The model fit results are quantified in terms of the percentage contribution of the different stellar components in a normalising bin defined as $4700 - 4800$ Å. Due to the uncertainties associated with the flux calibration, as well as the synthetic templates themselves, it is not correct to constrain the total flux in the normalising bin to be exactly the integrated flux of the observed spectrum in the bin. Therefore the CONFIT code allows the model flux in the normalising bin to vary up to 125% of the measured flux in that bin.

Potentially adequate fits to the SEDs (reduced $\chi^2 \lesssim 1.0$) can be found for combinations of small contributions of highly reddened YSP plus a very old stellar population, or large contributions of low reddened ISP with an old stellar component contributing much less to the overall stellar population in the aperture (i.e. the age/reddening degeneracy problem). To break this degeneracy we have examined detailed fits to the spectra, considering as valid those models that fit the important absorption features of the spectra adequately (e.g. CaII, K, G-band, higher order Balmer lines; see González Delgado et al. (2001); Holt et al. (2003); Rodríguez Zaurín et al. (2007)).

Table 3 summarizes the results obtained with the CONFIT code. Adequate fits for all 23 apertures extracted from the three slit positions are found with models combining two stellar components, an ISP and a YSP, with no need of an OSP. Figure 4 shows example fits for apertures selected with the aim of sampling a range of regions of the galaxy. Note that apertures Ap D and E for PA 160 sample the central 2.5 kpc diameter region, corresponding to dust lanes in the HST images. It is clear from the figure that the spectra extracted for these apertures are highly reddened. As well as the best-fitting models, detailed fits in the region of the Balmer lines (3700 – 4300Å) are also shown in Figure 4.

Overall, the results reveal a remarkable uniformity in the estimated stellar ages, with an ISP (0.5 Gyr $< t_{ISP} \leq 0.9$ Gyr) dominating the optical emission in all apertures, and a YSP ($\leq 0.1$ Gyr) making a relatively small contribution ($\leq 40\%$) in most apertures. However note that in the central 2.5 kpc of the galaxy (Ap D and E, PA 160), adequate fits are only found for combinations with a significant contribution of a YSP component (22 - 63%). In terms of reddening, while the results found in the extended regions are consistent with low intrinsic reddening, one or both stellar components must be highly reddened in the central 5 kpc of the galaxy, clearly indicating high concentrations of gas and dust in the nuclear regions.

At this stage, it is important to add a caveat about the spatial extent of the YSP component. In some of the extended regions of the galaxy (Ap E and F, PA 75°; Ap A, F and G PA 75; Ap A, PA 160), good fits are also found with a minimal contribution of a YSP template. This is consistent with the STARLIGHT results, where the ISP contribution found for these apertures is $\gtrsim 90\%$ of the total flux. On the other hand, a YSP component is always required to model the data for the apertures sampling the center of the galaxy. Therefore, while the presence of a YSP in the extended regions remains uncertain, the presence of such a component in the galactic center is essential. This result is consistent with the age of 10-100 Myr (Mundell et al., 2001) estimated for the central region of the galaxy, and also with the merger simulations predictions (Mihos & Hernquist, 1996; Barnes & Hernquist, 1996; Springel et al., 2005) for starbursts characteristic of the final stages of major gas-rich mergers.

Again, the results for the three large apertures show remarkable consistency, both with each other, and with the smaller aperture results presented in the tables.

Overall, the results obtained with CONFIT are broadly consistent with those of STARLIGHT approach, and clearly reinforce the idea that an ISP dominates the optical emission in Arp220.

### 3.3 The Hidden Starburst

Our analysis has so far concentrated on the optically visible star formation. It is interesting to consider the extent to which this represents the full extent of star formation in Arp220.

Previous studies based on radio observations (Smith et al., 1998) or the galactic superwind (Heckman et al., 1996; Mundell et al., 2001), have found star formation rates (SFR) up to $100 M_\odot yr^{-1}$ for Arp 220. An independent estimate of the SFR can be obtained using the published flux of the Brα line, $F(\text{Br}\alpha) = 1.8 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1}$ (Genzel et al., 1998). Using the IR extinction law of Indebetouw et al. (2003) and Rieke & Lebofsky (1983) along with the estimated visual extinction for the nuclear region of Arp 220 ($A_V \sim 45$ mag. Sturm et al., 1996; Genzel et al., 1998), we derive a Brα luminosity of $L(\text{Br}\alpha) = 9.2 \times 10^{43} \text{erg s}^{-1}$. Assuming Case B recombination theory we then derive an Hα luminosity of $L(\text{H}\alpha) = 3.3 \times 10^{43} \text{erg s}^{-1}$. It is now straightforward to estimate the SFR in the galaxy using the relationship between Hα luminosity and SFR given by Kennicutt (1998). We find a SFR $\sim 260 M_\odot yr^{-1}$, enough to power the entire mid- to far-IR luminosity observed in Arp220. Moreover, the absence of mid-IR, high-ionization emission lines ([NeV]14.322μm, OIV]25.890μm) and GALEX (Smith et al., 1998) suggests no hidden AGN activity, reinforcing the idea that starburst activity powers the ULIRG Arp220. In such a case, it is also possible to measure the SFR of the galaxy using the IR-luminosity (Kennicutt, 1998). For a value of $L_{IR} = 1.3 \times 10^{12} L_\odot$ for Arp 220 (Soifer et al., 1987) we obtain a SFR = 224 $M_\odot$...
yr\(^{-1}\) which is remarkably consistent with the value found using the Br\(\alpha\) flux.

However, there is no clear evidence for the presence of ongoing star formation activity at optical wavelengths, based on HII region-like optical emission line ratios (Veilleux et al., 1999). In order to measure the bolometric luminosity associated with the visible stellar populations detected in the optical, we added the spectra extracted for all the apertures of the region limited by the dashed-line box in Figure 1. Since our spectroscopic slits used do not cover the entire extent of the central region, a large aperture chosen to match the extent of the box was extracted from an HST ACS (F435W) image (HST proposal 9396, PI C. Wilson). We then scaled the combined spectrum to match the flux measured from the aperture, in order to account for possible flux losses. Assuming an ISP + YSP combination consistent with the modelling results of section 3.2 and correcting for reddening effects, we determined the bolometric luminosity of all the components in the scaled spectrum and added them, obtaining a total bolometric luminosity \(L_{\text{bol}} \sim 1.6 \times 10^{11} L_\odot\). This is an order of magnitude less than the mid- to far-IR luminosity of the source. Therefore, especially considering that not all the optical emission is absorbed by dust, it is clear that the stellar populations detected at optical wavelengths cannot power the far-IR luminosity of the source; most of the ongoing star formation in the nuclear regions is hidden by dust.

3.4 Summary of the key results

To summarize the main results, the modelling of our spectra provide evidence for three stellar populations in Arp220:

- **Dominant ISP.** We have found an intermediate-age stellar population, with ages \(0.3 \text{ Gyr} < t_{\text{ISP}} \leq 0.9 \text{ Gyr}\), that dominates the optical spectrum, extended across 65 arcsec (\(\sim 24\) kpc), and covering the measurable extent of the galaxy.
- **YSP component.** We have found a young stellar component, with ages \(t_{\text{YSP}} \leq 100\) Myr, with varying contributions across the galaxy, but particularly significant in the nuclear regions, where it is highly reddened.
- **Hidden Starburst.** Our results reinforce the idea that there is prodigious ongoing star formation activity that is hidden at optical wavelengths, likely to be related to the radio supernovae detected in the center of the galaxy (Smith et al., 1998), as well as the powerful mid to far-IR emission from this object.

4 DISCUSSION

4.1 Comparison with previous results

Wilson et al. (2006) found evidence for a centrally located YSP (\(\leq 10\) Myr) and an intermediate-age (\(\sim 300\) Myr) stellar population spread towards the north of the galaxy in their photometric study of the cluster populations in Arp 220. These results are broadly consistent with the results presented in this paper. In addition, we find evidence for ISPs at all locations in the galaxy.

There have been relatively few attempts in the past to study the stellar populations in the diffuse light of ULIRGs. Canalizo & Stockton (2000a, 2003) found stellar ages ranging from currently ongoing starburst activity to poststarburst ages of \(\geq 300\) Myr in their sample of “transition QSOs” — objects that may represent a transitional stage between ULIRGs and QSO. The ages found for the dominant stellar populations in Arp220 are generally older than 300 Myr, although Canalizo & Stockton (2000a, 2001) used only one stellar component for their modelling.

More recently, Rodríguez Zaurín et al. (2007) applied the same techniques used here to the ULIRG/radio galaxy PKS1345+12. Overall, the results found in their paper are consistent with the results found here for Arp 220, with a mixture of YSP and ISP components. However, precise age determination for the ISP component is more difficult in PKS1345+12 because of the presence of a strong OSP component.

We are currently analyzing the optical spectra of a sample of 40 ULIRGs (Rodriguez et al., 2007, in prep). We find that the modelling results are consistent with a combination of YSP + ISP components for the majority of the objects in our sample. However, we find that the YSPs found in these galaxies make a larger contribution than in the case of Arp220, and sometimes dominate the optical spectra. Finally, similar results in terms of the mix of stellar populations have recently been obtained in detail spectroscopic studies of LIRGs (González Delgado, 2007).

4.2 The origin of the ISPs

In order to use studies of the stellar populations to investigate star forming histories in major galaxy mergers it is important to understand the extent to which the stellar populations have been formed during the merger. A potential issue is contamination by the young stellar populations present in the galaxy disks prior to the star of the merger. As a first approach to investigate the origin of the ISPs we used the CONFIT code and combined unreddened Sa, Sb and Sc galaxy template spectra (Kinney et al., 1998) with a stellar population with ages in the range 0.001 \(\leq \text{age} \leq 5\) Gyr and reddenings 0.0 \(\leq E(B-V) \leq 2.0\).

No good fits were found for combinations of Sa, Sb or Sc galaxy templates without a significant additional contribution of a YSP or an ISP component. However, the Kinney et al. (1996) templates represent an average for several galaxies of the same morphological type, and each type encompasses a range of individual galaxy spectra, some of which deviate substantially from the averaged SED. Therefore, although the modelling results obtained using this combination suggest that the stellar populations detected in the optical for the ULIRG Arp220 have been formed during the merger event rather than captured, we cannot entirely rule out the idea that the ISPs detected in the galaxy represent the disrupted disks of one or more of the merging galaxies.

Another way to address this issue is to compare the mass of YSPs in late type spiral galaxies, the likely progenitor galaxies, with the values found here for the ISPs in Arp...
PA 160: Ap A: 0.7 Gyr ISP, E(B − V) = 0.1 + 0.01 Gyr, E(B − V) = 0.3

Figure 4.
Figure 4. Detailed fits to the spectra extracted for some of the apertures sampling the different regions of the galaxy (see Figure 1 for the location of the extraction apertures). The green and blue lines are the ISP and YSP components respectively, while the red lines are the sum of both. It is clear from the figure that a variety of redenings is required to fit the data for the different apertures. Also shown in the figure are detailed fits of the wavelength range 3700 Å – 4300 Å (plots on left). The fluxes are presented in wavelength units.
220. The reason to focus only on YSPs in the parent galaxies is that, if the star formation in the disks is truncated during the merger, these are the populations which may evolve into ISPs detected today in Arp 220. Since our three slit positions do not cover the full extent of the object, we used the apparent magnitude of the galaxy in the V band, $m_V = 13.2$ (Taylor et al., 2005), and applied the same techniques described in section 3.4 to account for possible slit losses. We then assumed the same values for the contribution of each component, as defined in Section 3.

### Table 2. Modelling results obtained using the STARLIGHT code with the González Delgado et al. (2005) synthetic SEDs. Col (1): Slit PA. Col (2): Aperture label. Apertures D and E from PA 160 sample the nuclear regions of the galaxy Col (3): Width of the aperture (the centroid of Ap D is chosen to be the reference point for all the slit positions). Col (4): The intrinsic reddening value obtained for the best fitting models assuming the same extinction for all the stellar components. Cols (5), (6) and (7): The flux percentage at 4020 Å.

| Slit   | Ap A                 | Ap B       | Ap C       | Ap D       | Ap E       | Ap F       | Ap G       | Ap TOTAL  |
|--------|----------------------|------------|------------|------------|------------|------------|------------|-----------|
| PA 160 | -12.6 to -8.2        | -8.2 to -5.4 | -5.4 to -1.8 | -1.8 to 1.8 | 1.8 to 4.6 | 4.6 to 8.6 | 8.6 to 22.6 | -24.4 to 28.4 |
|        | 0.0                  | 0.1        | 0.4        | 0.8        | 0.7        | 0.4        | 0.2        | 0          |
|        | 0                    | 100        | 96         | 34         | 63         | 71         | 91         | 80         |
| PA 75  | -26.6 to -8.6        | -8.6 to -4.2 | -4.2 to -1.4 | -1.4 to 1.4 | 1.4 to 5.0 | 5.0 to 10.2 | 10.2 to 34.6 | -29.4 to 35.8 |
|        | 0.3                  | 0.5        | 0.5        | 0.4        | 0.4        | 0.4        | 0.3        | 0          |
|        | 10                   | 68         | 77         | 88         | 84         | 87         | 91         | 87         |
| PA75*  | -19.2 to -12.0       | -12.0 to 5.2 | -5.2 to -2.8 | -2.8 to 2.8 | 2.8 to 17.6 | 17.6 to 38.4 | 23.2 to 45.6 | 0          |
|        | 0.2                  | 0.2        | 0.2        | 0.2        | 0.2        | 0.2        | 0          | 0          |
|        | 16                   | 96         | 96         | 89         | 96         | 93         | 92         | 0          |

In terms of gas content, Scoville et al. (1997) found a mass of $\sim 3 \times 10^{10} \text{M}_\odot$ for the H$_2$ mass of Arp 220. However, they used a standard Galactic CO-to-H$_2$ ratio, which is likely to overestimate the molecular mass M(H$_2$) by a factor of three (Solomon et al., 1997). On the other hand, an upper limit for the HI mass value for Arp220 is $5.0 \times 10^9 \text{M}_\odot$ (Mirabel & Sanders, 1988). Therefore, the total gas mass in the galaxy, M(H$_2$ + HI), is of order of $1.5 \times 10^{10} \text{M}_\odot$. In comparison, the median value of the HI mass content of Sc galaxies is $0.8 \times 10^{10} \text{M}_\odot$ (Roberts & Haynes, 1994). Assuming a typical H$_2$/HI mass ratio of 0.7 (Young & Knezek, 1983) for such galaxies, we find a gas mass content of M(H$_2$ + HI) $\sim 1.4 \times 10^{10} \text{M}_\odot$ for a typical Sc galaxy. Therefore, we conclude that it is possible for a merger of two typical spiral galaxies to account for the gas content estimated in Arp220 provided that a large fraction of the gas is not ejected during the merger (Di Matteo et al., 2007) or transformed into stars. However if a substantial proportion of the ISPs are formed in the merger, then the total amount of gas required is much larger, implying a merger between two Sc galaxies.
in the upper 25% of the HI mass range \citep{RobertsHaynes1994}.

### 4.3 Comparison with models

Arp220 is a double nucleus system with a separation of 0.95 arcsec, corresponding to \approx 345 pc, that exhibits tidal tails in the optical. The morphology of the galaxy suggests that it is in the final stages of the merger event, just before the two nuclei coalesce. In this section we will compare the results found in this paper with the prediction of the models for the star formation activity at such a stage of a merger event.

In general, simulations predict two epochs of starburst activity \citep{MihosHernquist1996, BarnesHernquist1996, Springeletal2003} in major gas-rich mergers: the first occurring just after the first encounter, and the second, more intense, episode towards the end of the merger, when the nuclei coalesce. However, both the time lag and the relative intensity of the peaks of starburst activity during the merger event depend on several factors: the presence of bulges, feedback effects, gas content and orbital geometry. For example, the presence of a bulge acts as a stabilizer of the gas against inflows and formation of bar structures, allowing stronger starburst activity towards the end of the merger event \citep{MihosHernquist1996}.

\begin{table}[!h]
\centering
\begin{tabular}{cccccccc}
\hline
 & Width of the Aperture (arcsec) & Age of ISP (Gyr) & \(E(B-V)\) & Age of YSP (Gyr) & \(E(B-V)\) & \%YSP of total flux & \\
\hline
\textbf{PA 160} & & & & & & & \\
Ap A & -12.6 to -8.2 & 0.6 - 0.7 & 0.0 - 0.2 & < 0.1 & 0.0 - 0.2 & < 5 & \\
Ap B & -8.2 to -5.4 & 0.5 - 0.7 & 0.0 - 0.2 & < 0.1 & 0.0 - 0.3 & < 5 & \\
Ap C & -5.4 to -1.8 & 0.5 - 0.7 & 0.3 - 0.5 & < 0.1 & 0.0 - 1.0 & 5 - 15 & \\
Ap D & -1.8 to 1.8 & 0.5 - 0.9 & 0.0 - 1.0 & < 0.08 & 0.9 - 1.8 & 30 - 63 & \\
Ap E & 1.8 to 4.6 & 0.5 - 0.9 & 0.2 - 0.6 & < 0.06 & 0.9 - 1.6 & 22 - 47 & \\
Ap F & 4.6 to 8.6 & 0.5 - 0.7 & 0.2 - 0.6 & < 0.08 & 0.0 - 1.5 & 5 - 36 & \\
Ap G & 8.6 to 22.6 & 0.5 - 0.7 & 0.0 - 0.3 & < 0.07 & 0.0 - 0.7 & 5 - 20 & \\
\textbf{APTOTAL} & -24.4 to 28.4 & 0.5 - 0.7 & 0.2 - 0.6 & < 0.1 & 0.0 - 1.5 & 5 - 35 & \\
\textbf{PA 75} & & & & & & & \\
Ap A & -26.6 to -8.6 & 0.5 - 0.7 & 0.2 - 0.5 & < 0.1 & 0.0 - 2.0 & < 20 & \\
Ap B & -8.6 to -4.2 & 0.5 - 0.7 & 0.2 - 0.6 & < 0.1 & 0.0 - 1.0 & 5 - 25 & \\
Ap C & -4.2 to -1.4 & 0.5 - 0.7 & 0.2 - 0.6 & < 0.05 & 0.0 - 1.2 & 5 - 30 & \\
Ap D & -1.4 to 1.4 & 0.5 - 0.7 & 0.2 - 0.6 & < 0.06 & 0.0 - 1.5 & 5 - 25 & \\
Ap E & 1.4 to 5.0 & 0.5 - 0.7 & 0.2 - 0.5 & < 0.05 & 0.0 - 2.0 & < 30 & \\
Ap F & 5.0 to 10.2 & 0.6 - 0.9 & 0.1 - 0.4 & < 0.1 & 0.0 - 1.2 & < 25 & \\
Ap G & 10.2 to 34.6 & 0.7 - 0.9 & 0.0 - 0.3 & < 0.1 & 0.0 - 0.8 & < 25 & \\
\textbf{APTOTAL} & -29.4 to 35.8 & 0.5 - 0.7 & 0.2 - 0.5 & < 0.1 & 0.0 - 1.2 & 5 - 25 & \\
\textbf{PA75} & & & & & & & \\
Ap A & -19.2 to -12.0 & 0.5 - 0.7 & 0.0 - 0.3 & < 0.06 & 0.0 - 0.6 & 10 - 35 & \\
Ap B & -12.0 to 5.2 & 0.5 - 0.7 & 0.0 - 0.3 & < 0.1 & 0.0 - 1.5 & 5 - 25 & \\
Ap C & -5.2 to -2.8 & 0.5 - 0.7 & 0.0 - 0.3 & < 0.1 & 0.0 - 1.5 & < 40 & \\
Ap D & -2.8 to 2.8 & 0.5 - 0.8 & 0.0 - 0.3 & 0.06 & 0.0 - 1.5 & < 40 & \\
Ap E & 2.8 to 17.6 & 0.6 - 0.9 & 0.0 - 0.3 & < 0.06 & 0.0 - 1.0 & < 25 & \\
Ap F & 17.6 to 38.4 & 0.6 - 0.9 & 0.0 - 0.3 & < 0.1 & 0.0 - 2.0 & < 15 & \\
\textbf{APTOTAL} & -23.2 to 45.6 & 0.5 - 0.8 & 0.0 - 0.3 & < 0.06 & 0.0 - 1.5 & 5 - 30 & \\
\end{tabular}
\caption{Modelling results obtained using the CONFIT code with the Bruzual & Charlot (2003) synthetic SEDs. Col (1): Slit PA. Col (2): Aperture label. Apertures D and E from PA 160 sample the nuclear regions of the galaxy Col (3): Width of the aperture (the centroid of Ap D is chosen to be the reference point for all the slit positions). Col (4): Range of ages for the ISP component. Col (5): Range of intrinsic \(E(B-V)\) values for the ISP component. Col (6): Upper limits for the ages of the YSP component. Col (7): Same as column 5 for the YSP component. Col (8): Upper limits for the contribution in flux of the YSP to the model in the normalising bin (4700\AA~— 4800\AA), for those cases for which an ISP can model the data with a negligible contribution of a young component.}
\end{table}

On the other hand, AGN feedback effects (e.g. quasar-driven winds) disrupt the gas surrounding the black hole, acting against the star formation activity \citep{Springeletal2005}. In the case of Arp220, we derive star formation rates of \approx 260 M_\odot yr^{-1}, consistent with a starburst being responsible for the IR luminosity of the galaxy and there is no evidence for AGN activity \citep{Genzeletal1998}. Based on the results of the simulations \citep{Springeletal2005}, highly gas-rich disc galaxies must be involved in the merger event to account for such high star formation rates. In this context, the results found in the previous section are consistent with the model predictions. It is possible that the dominant ISPs detected in Arp220 are associated with the first enhancement in star formation activity that occurs in the early stages of the merger, coinciding with the first encounter between the merging nuclei. However, because of the potential contamination from stars in the disrupted disks of the merging galaxies (section 4.2), the fraction of ISPs formed in the merger is not known with any accuracy. On the other hand, the YSPs detected in the center of the galaxy, as well as the ULI RG activity, are likely to be related to the major enhancement of the activity as the two nuclei coalesce in the final stages of the merger. It is notable that the ages of the YSP (\(t_{YSP} < 0.1\) Gyr) are consistent with the 0.1
5 CONCLUSIONS

The results presented in this paper demonstrate the utility of spectroscopic studies of the diffuse light for investigating the evolution of the stellar populations in ULIRGs.

We have found evidence for a complex star forming history in the ULIRG Arp 220, with at least two distinct episodes of starburst activity. The results are consistent with an intermediate-age stellar population of age $0.1 < \tau_{ISP} \leq 0.9$ Gyr, dominating the optical emission throughout the body of the galaxy. We have also detected young ($\lesssim 100$ Myr) stellar populations (YSPs) located in the central $\sim 2.5$ kpc that contribute significantly to the optical emission. This latter population is likely to be related to the last enhancement of the activity towards the end of the merger event.

On the other hand, we have estimated that the bolometric luminosity accounted by the optically visible stellar populations and compared it with the IR-luminosity of the galaxy. We conclude that we are not directly detecting the bulk of the starburst activity responsible for the ULIRG phenomenon in Arp220, which is likely to be related to the radio supernovae found by Smith et al. (1998), representing another “extra” episode of star formation activity apart from the two suggested by our modelling results. It is clear that our results for Arp220 are consistent with the emerging evidence for a complex and multimodal star formation activity in merging systems (The Antennae: Whitmore et al. (1999), NGC7252: Maraston et al. (2001), PKS1345+12: Rodríguez Zaurín et al. 2007).

In terms of reddening, while the presence of highly reddened stellar component is unlikely in the extended regions of the galaxy, high reddening values are required to match the data for the apertures sampling the nuclear regions, coinciding with dust lanes in the HST images. Our results show the importance of accounting for reddening when trying to model stellar populations in star forming galaxies.

Finally, we note that the modelling results for the three large apertures, representing the integrated light of the galaxy, are consistent with those of the detailed study based on smaller apertures. This gives confidence to studies of ULIRGs at medium and high redshifts, suggesting that age measurements based on relatively large aperture studies of the diffuse light at such redshifts, are representative of the stellar populations of the galaxies as a whole.

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