Arp 220: EXTINCTION AND MERGER-INDUCED STAR FORMATION

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ABSTRACT

We analyze new spatially resolved integral field spectroscopic H- and K-band data at a resolution of 0.3 (100 pc) and reanalyze interferometric CO(2–1) line observations of the prototypical merging system Arp 220. We find that the majority of the K-band luminosity is due to a 10 Myr old starburst, with a significant contribution from an underlying ∼1 Gyr old stellar population and a small contribution from stars ∼8 Myr old. The Calzetti et al. reddening law provides the best fit to photometric data points spanning 0.45–2.12 μm. Furthermore, estimates of the bolometric luminosity from IRAS fluxes in conjunction with our stellar population analysis indicate that we observe less than 10% of the emitted K-band light. The stellar and CO(2–1) kinematic center of the western nucleus coincides with the compact hot dust emission, indicating that the latter marks the center of the gravitational potential. In the eastern nucleus, the CO(2–1) data are well matched by a model in which the gas orbits around the peak of the dust emission. This, and the similarity of the K-band tracer kinematics, shows that despite the irregular morphology, the eastern nucleus is also a kinematically coherent structure. Comparison of the extinction map with EWCO and EWBr maps indicates that the lower half of the eastern nucleus is significantly more extincted than the upper half, suggesting that the lower half is buried in the larger scale gas disk.

Key words: galaxies: active – galaxies: individual (Arp 220) – galaxies: interactions – galaxies: kinematics and dynamics – galaxies: starburst – infrared: galaxies

Online-only material: color figures

1. INTRODUCTION

Local ultraluminous infrared galaxies (ULIRGs, with $L_{IR} \gtrsim 10^{12} L_\odot$; Sanders & Mirabel 1996) have received considerable attention since their discovery by IRAS (Neugebauer et al. 1984). They are almost exclusively major mergers (Sanders et al. 1988; Sanders & Mirabel 1996; Veilleux et al. 2002; Jogee 2006) and widely held to constitute a key epoch in the transformation of gas-rich spiral galaxies to elliptical galaxies (e.g., Hopkins et al. 2006). Although not making a significant contribution to the cosmic energy budget at current times, their relative importance increases toward higher redshifts (e.g., Caputi et al. 2007; Magnelli et al. 2009, 2010). Thus, the study of local ULIRGs is important for several reasons: to properly understand the major merger process believed to trigger quasar activity and result in elliptical galaxies, and as local analogs of the most luminous high-z galaxies (e.g., Engel et al. 2010b).

Arp 220 ($L_{IR} = 1.4 \times 10^{12} L_\odot$; Soifer et al. 1987) is the closest ULIRG representative ($D = 73$ Mpc; $z = 0.018$, $1'' = 352$ pc) and thus a unique laboratory for the investigation of this important class of galaxies. As such, it has been extensively studied and is widely regarded as the prototypical ULIRG. It is an advanced merger; tidal tails and distortions are observed at optical wavelengths and in H I emission (Arp 1966; Joseph & Wright 1985; Hibbard et al. 2000). There is evidence for a galactic-scale outflow from H z and soft X-ray observations (Armas et al. 1990; Heckman et al. 1996; McDowell et al. 2003). In the center, two nuclei are discernible with a separation of ∼0.4 kpc in the near-infrared (Scoville et al. 1998), millimeter (Scoville et al. 1997; Downes & Solomon 1998; Sakamoto et al. 1999; Downes & Eckart 2007), and radio (Mundell et al. 2001) regimes. There is also a more extended (kpc-scale), rotating gas disk (Downes & Solomon 1998; Sakamoto et al. 1999, 2009; Mundell et al. 2001; Wiedner et al. 2002). Arp 220 is very gas-rich; Scoville et al. (1997) measure a molecular gas mass of $\sim 9 \times 10^9 M_\odot$, concentrated in the central 750 pc—implying an astonishing molecular gas surface density of $5 \times 10^4 M_\odot$ pc$^{-2}$. It therefore comes as no surprise that obscuration is severe for this system; estimates for $A_V$ range from 50 to 1000 (Sturm et al. 1996; Downes & Solomon 1998), and even at near-infrared wavelengths obscuring dust lanes are visible (Scoville et al. 1998). Observations of CO(3–2) and the 860 μm continuum (Sakamoto et al. 2008) and of CO(6–5) and the 435 μm continuum (Matsushita et al. 2009) indicate substantial dust optical depths even at submillimeter wavelengths. These extreme levels of extinction have hindered a definitive determination of the power source of Arp 220; a significant contribution to its prodigious luminosity comes from a starburst (Sturm et al. 1996; Lutz et al. 1996, 1998; Genzel et al. 1998), but there is also significant (and possibly dominant) dust emission from heavily obscured central star formation or perhaps an active galactic nucleus (AGN; Spoon et al. 2004). The presence of a deeply dust-enshrouded major nuclear power source is confirmed by millimeter observations; most recently, Sakamoto et al. (2008) estimated the bolometric luminosity of the 50–80 pc core within the western nucleus to be at least $2 \times 10^{11} L_\odot$ and possibly as much as $\sim 10^{12} L_\odot$. The high obscuration has prevented the confirmation or rejection of a possible active nucleus through X-ray observations (Iwasawa et al. 2001, 2005; Clements et al. 2002); the obscuring column density is of order $N_H \sim 10^{25}$ cm$^{-2}$ (Iwasawa et al. 2001; Sakamoto et al. 2008). Downes & Eckart (2007) interpret the very compact dust continuum emission in the western nucleus as being heated by a black hole accretion disk, whereas Sakamoto et al. (2008) contend that the starbursting west nuclear disk must have in its center a dust enshrouded AGN or a very young starburst equivalent to hundreds of super star clusters.

Since Arp 220 is the ULIRG most frequently used as a starburst galaxy template, it is vital to understand its power source and star formation history. A photometric analysis by
Wilson et al. (2006) of HST UBVI observations showed that the central cluster population divides into two groups: one with ages \(<10\) Myr and one with ages \(\sim 300\) Myr. However, it must be kept in mind that due to photometric uncertainties, the age/reddening degeneracy limits the accuracy of such work. Rodriguez Zaurin et al. (2008) use optical spectroscopic observations of the extended diffuse light along three slit positions for a stellar population analysis; they find the optical spectrum to be dominated by an intermediate-age stellar population (0.5–0.9 Gyr), and a young stellar population (<100 Myr) which has an increasing contribution toward the central part of the galaxy. Besides the extinction limitations afflicting all optical-wavelength observations of dusty galaxies, it must be cautioned that only one of their slits covers the central region, from which the vast majority of the luminosity is emitted, and hence that their results may be biased toward the star formation history of the subdominant outer regions. Parra et al. (2007; see also Rovilos et al. 2005; Lonsdale et al. 2006) investigate radio supernovae and supernova remnants in the nuclear region of Arp 220, finding that they are indicative either of a radically different stellar initial mass function, or a very short, intense burst of star formation \(<3\) Myr ago.

Here, we use adaptive optics near-infrared integral field spectroscopy data and interferometric mm CO(2–1) and continuum observations to investigate the star formation history, the extinction, and the nature and orientation of the two nuclei.

In Section 2, we introduce the data and data analysis procedures. In Section 3, we investigate the star formation history in the SINFONI field of view (FOV), and in Section 4 we look at the extinction in the near-infrared. We then focus on the western (Section 5) and eastern (Section 6) nuclei. We put this together in a coherent picture of the nuclear region (Section 7), before summarizing and concluding in Section 8.

### 2. OBSERVATIONS AND DATA PROCESSING

#### 2.1. SINFONI Data

2.1.1. Observations and Reduction

Observations of Arp 220 were performed on the nights of 2007 March 7 and April 18–21 on Cerro Paranal, Chile, at the Very Large Telescope (VLT) with SINFONI. SINFONI is a near-infrared integral field spectrometer (Eisenhauer et al. 2003) which includes a curvature-based adaptive optics system (Bonnet et al. 2004) and can operate with the VLT’s laser guide star facility (Bonaccini Calia et al. 2006; Rabien et al. 2004). The laser guide star was used for these observations, without tip-tilt correction due to lack of a suitable tip-tilt star. SINFONI’s 0′05 \(\times\) 0′10 pixel scale was used, giving a 3′2 \(\times\) 3′2 FOV. The science data and standard star observations were reduced using the SPRED software package (Abuter et al. 2006). Telluric correction and flux calibration of the reconstructed data cubes were performed using these standard star frames. Figure 1 shows spectra from three different positions of the Arp 220 nuclear region.

#### 2.1.2. PSF Estimation

Several avenues exist to estimate the point-spread function (PSF hereafter) of adaptive optics data. Here we employ the method outlined by Davies (2008) and used, e.g., by Mueller Sánchez et al. (2006) and Engel et al. (2010a), which proceeds by comparing the data for which the PSF is not known, denoted \(I_{\text{low}}\), here, to higher resolution data with known PSF \(I_{\text{high}}\). Since an observed image is the convolution of the instrumental PSF with the intrinsic on-sky image, \(I_{\text{obs}} = I_{\text{intr}} \otimes \text{PSF}\), the PSF of the AO data can be estimated by finding the broadening function \(B\) which, applied to the higher resolution image, yields the best match to the AO image; \(I_{\text{low}} = I_{\text{high}} \otimes B\). Since \(I_{\text{intr}}\) is the same for both \(I_{\text{low}}\) and \(I_{\text{high}}\), the PSF of \(I_{\text{low}}\) can be estimated by convolving the PSF of the high-resolution image with the broadening function \(B\); \(\text{PSF}_{\text{low}} = \text{PSF}_{\text{high}} \otimes B\).

In our case, we use HST NICMOS 2.16 \(\mu\)m observations retrieved from the HST (Hubble Space Telescope) archives. Figure 2 shows our SINFONI data, the HST data (rotated and resampled to the SINFONI pixel scale), and the broadened HST image. We find the PSF to be well represented by an almost perfectly symmetric Gaussian with major axis oriented 4° east of north and FWHM 0′30 \(\times\) 0′31—a good performance for laser guide star assisted adaptive optics without a tip-tilt star (Davies et al. 2008).
to the large spatial variations in EWCO seen in this system and an excellent match everywhere is almost impossible to find, due to finding a single template (or a composite template) that provides in errors of at most only a few percent. Here, the template is the continuum level to zero—the choice of template star is not discussed in Engel et al. (2010a), with this method—setting M3 III star HD 176617, was prepared analogously. As we continue level to zero. A stellar template spectrum, of the K-band tracers coincide at the same location (unlike in NGC 6240 (Engel et al. 2010a).

In order to achieve a minimum signal to noise, we spatially binned each spectral plane of our reduced data cube using an optimal Voronoi tessellation (Cappellari & Copin 2003), which bins pixels together into groups by accreting new pixels to each group until a preset signal-to-noise cutoff is reached.

The signal-to-noise cutoff was chosen so as not to compromise spatial resolution in the central regions (i.e., such that no binning was performed there), but at the same time extending the region in which meaningful analyses can be performed. As a result of this, the outer regions in, e.g., the velocity maps, appear in blocks, rather than individual pixels.

2.1.3. Spatial Binning

In order to achieve a minimum signal to noise, we spatially binned each spectral plane of our reduced data cube using an optimal Voronoi tessellation (Cappellari & Copin 2003), which bins pixels together into groups by accreting new pixels to each group until a preset signal-to-noise cutoff is reached.

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2.1.4. Extracting Stellar Kinematics

The $K$ band covers the stellar CO absorption bandheads longward of $2.29 \mu$m whose sharp blue edges are very sensitive to stellar motions. Here we utilize CO 2–0 and CO 3–1 to derive two-dimensional maps of the stellar velocity and dispersion. After normalizing the spectra with respect to a linear fit to the line-free continuum, we subtract unity and thus set the continuum level to zero. A stellar template spectrum, of the M3 III star HD 176617, was prepared analogously. As we discuss in Engel et al. (2010a), with this method—setting the continuum level to zero—the choice of template star is not critical, with even significantly mismatched templates resulting in errors of at most only a few percent. Here, the template is matching the bandheads quite well. We furthermore note that finding a single template (or a composite template) that provides an excellent match everywhere is almost impossible to find, due to the large spatial variations in EWCO seen in this system and also, e.g., in NGC 6240 (Engel et al. 2010a).

In order to obtain the two-dimensional velocity and dispersion maps, we fit the template to the spectrum of each spatial pixel (spaxel hereafter) by convolving it with a Gaussian, varying the Gaussian parameters until a best match is achieved. The Gaussian position and width then yield the stellar velocity and dispersion at that spaxel. During the fitting, the spectral regions covering the steep edges of the bandhead at all expected stellar velocities are given fivefold weight, in order to focus the fit on the kinematics rather than details in the spectrum. The spectral ranges used to compute the CO$_{2-0}$ bandhead equivalent width (EW$_{\text{CO}}$ hereafter) are those of Förster Schreiber (2000); these ranges are also used by the stellar synthesis code STARS employed later. We note that we do not attempt to extract the Gaussian–Hermite terms $h_1$ and $h_4$, since the signal to noise across most of our spectra is not sufficient to include these in the fit.

The resulting final maps of stellar velocity, dispersion, and EW$_{\text{CO}}$ are displayed in Figure 3.

2.1.5. $H$- and $K$-band Gas Tracers

We derive emission, equivalent width (EW), velocity, and velocity dispersion maps of H$_2$ 1-0S(1) ($\lambda = 2.1218 \mu$m), HeI ($\lambda = 2.0581 \mu$m), Pa$\alpha$ ($\lambda = 1.8751 \mu$m), [Fe II] ($\lambda = 1.6440 \mu$m), Br$\gamma$ ($\lambda = 2.1662 \mu$m), and Br$\delta$ ($\lambda = 1.9445 \mu$m), by fitting Gaussians to the lineshapes. The results are shown in Figure 4.

2.2. Plateau de Bure Interferometer Data

We also analyze $^{12}$CO($J = 2-1$) line emission and 1.3 mm dust continuum emission observations from the IRAM millimeter interferometer, located on the Plateau de Bure, France, at an altitude of 2550 m (Guilloteau et al. 1992). These observations were first analyzed and published by Downes & Eckart (2007), and we refer the reader to this publication for the technical details. These authors find evidence for a hot dust source in the western nucleus, which they interpret as being heated by an AGN accretion disk, the best evidence for a black hole in the central region of Arp 220 to date. Since the absolute astrometry between the PdBI and the SINFONI data sets is not precise, we anchor the SINFONI and PdBI data with respect to each other by assuming that the flux peaks of the western nucleus are coincident. This assumption is justified by the fact that in the western nucleus, all the K-band tracers coincide at the same location (unlike in the eastern nucleus), and hence it is plausible to expect that the cold gas emission also peaks at the same position. We derive a velocity map by fitting Gaussians to the line shapes; the result is displayed in Figure 5.

3. STAR FORMATION HISTORY AND STELLAR POPULATIONS

In this section, we investigate the star formation history and the composition of the stellar population, using observables and the stellar synthesis code STARS (Sternberg 1998; Sternberg et al. 2003; Förster Schreiber et al. 2003; Davies et al. 2003, 2005, 2006, 2007). In the following, we use spatially averaged measurements to investigate the composition of the stellar population. Since we are summing over a large spatial area, we can be sure to cover a large number of individual star clusters (which may have started forming stars at slightly different times), and hence to be probing the average star formation properties. Our primary diagnostics are the EW$_{\text{CO}}$ and the Br$\gamma$ flux and EW$_{\text{Br}\gamma}$. The EW$_{\text{CO}}$ map is shown in the last
panel of Figure 3, the Brγ maps are displayed in Figure 6. In Figure 7, we show the evolution of EWCO, EWBrγ, and $L_{\text{bol}}/L_K$ for a number of starbursts with different decay timescales. We furthermore use dynamical mass estimates of the nuclei (details can be found in Sections 5.3 and 6.2) and predictions of the mass-to-light ratios of different stellar populations (Figure 7). In what follows, we show that a single stellar population cannot account for the observed diagnostics. Instead we find that three distinct populations are required: a 10 Myr old starburst accounting for over half the observed luminosity, a significant contribution from an old ($\gtrsim$1 Gyr) stellar population, and a rather smaller population of very young stars, responsible for the Brγ emission.

3.1. A 10 Myr Old Starburst...

We observe EWCO to be $\gtrsim$14 Å everywhere, and $\gtrsim$16 Å on the nuclei; as can be seen from Figure 7, only an instantaneously decaying (“delta”-) starburst 10 ± 2 Myr old can produce such large values of EWCO. Do these stars account for the entire stellar luminosity and mass, or are there significant contributions from other stellar populations? We can estimate the luminosity contribution of any stars not belonging to this 10 Myr old starburst population by noting that the theoretically possible upper limit to EWCO is 17 Å. This allows us to calculate the luminosity contribution from a stellar population with smaller EWCO that may be diluting it. We note that this is strictly speaking only an upper limit, since we do not know the intrinsic EWCO of the starburst population. However, this intrinsic value is likely quite close to 17 Å, since this is what is measured in between the two nuclei, where the dilution from any putative older stellar population associated with the nuclei would be minimal. Hence our “upper limit” to the non-starburst luminosity is in fact more likely to be a reasonable estimate.

3.2. …and a Younger Stellar Population?

Both the presence of radio supernovae (Parra et al. 2007) and our Brγ maps clearly indicate the presence of young stars—only very young ($\lesssim$8 Myr) stars are hot enough to excite hydrogen sufficiently to emit the Brγ flux. An important question is whether this population contributes to the K-band continuum.
Figure 4. Flux, EW, velocity, and velocity dispersion maps for a number of H- and K-band tracers (cf. Section 2.1.5).
(A color version of this figure is available in the online journal.)
Figure 5. CO(2–1) flux (left, with contours showing the K-band continuum) and velocity map (right, contours tracing the CO(2–1) flux). The bar indicates 1″. North is up and east is to the left.

(A color version of this figure is available in the online journal.)

Figure 6. Brγ flux (left) and EW (right). Contours trace the Brγ flux. The bar indicates 1″. North is up and east is to the left.

(A color version of this figure is available in the online journal.)

Figure 7. Evolution of EW_{CO}, EW_{Brγ}, L_{bol}/L_K, and M/L_K, computed with STARS, for an instantaneously decaying starburst (red), starbursts with decay timescale 10 Myr (green) and 100 Myr (blue), and continuous star formation (black). As can be seen, only a ∼10 Myr old “delta”-starburst can produce EW_{CO} ≳ 14 Å.

(A color version of this figure is available in the online journal.)
We thus first investigate the possibility that a population of stars younger than 10 Myr may be diluting the CO bandheads of the 10 Myr starburst population; these stars would have $EW_{CO} \approx 0$ Å (Figure 7). In this case, the younger stars would contribute $\sim 10\%$ of the $K$-band luminosity. Below (Section 4), we calculate that if the assumption of younger ($< 10$ Myr) stars diluting the CO bandheads is correct, then we are only seeing $\approx 20\%$ of the actually emitted (no reddening-correction) $K$-band luminosity. For a 10 Myr old instantaneously decaying starburst, STARS predicts a luminosity. For a 10 Myr old instantaneously decaying starburst, $\approx$diluting the CO bandheads is correct, then we are only seeing $\sim \frac{C}{75}$ a factor $\gtrsim \frac{C}{75}$ of the 10 Myr starburst population; these stars would have the theoretical possible maximum of $\sim 17$ Å, we can exclude the possibility of any significant hot dust emission.

When accounting for the obscuring effects of dust, the dust is most commonly assumed to be either spatially uniformly mixed with the stars (mixed model) or to form a screen between the observed stars and the observer. Or, one can use the empirically derived reddening law of Calzetti et al. (2000). In cases of strong obscuration, the mixed model may be insufficient to account for the reddening, since it saturates beyond a certain level of extinction. In order to determine which method is appropriate for Arp 220, we obtained archival HST images spanning a wavelength range of $0.45$–$2.12$ μm and extracted photometric data points at a number of locations using 0.15 radius apertures. We then reddened a synthetic stellar population spectrum (corresponding to the star formation history determined in Section 3), using each reddening prescription outlined above, until it fit those data points. The results can be seen in Figure 8—as expected, the mixed model was insufficient to account for the strong extinction of Arp 220. The screen model results in a decent match, but the Calzetti et al. (2000) reddening law clearly produces the best results. We note that Engel et al. (2010a) arrive at the same conclusion for NGC 6240. Here, the screen extinction law also yields a somewhat lower $F_{obs}/F_{em}$ than the Calzetti et al. (2000) reddening law.

In order to quantify the reddening in Arp 220, we fitted a stellar template to the line-free continuum, using the Calzetti et al. (2000) reddening law. In Figure 9, we show the resulting map of $F_{obs}/F_{em}$ at 2.12 μm, and of the corresponding optical extinction $A_V$, obtained by calculating $F_{obs}/F_{em}$ at 0.55 μm and converting to extinction via $A_V = -2.5 \log(F_{obs}/F_{em})$.

We also derived the reddening using molecular hydrogen emission lines. For case B recombination at $T = 10,000$ K and $n_e = 10^4$ cm$^{-3}$, the line flux ratio of Paα and Brγ is 12.2; by comparing this to the actually observed line ratio, the relative reddening can be deduced. Again using the Calzetti et al. (2000) reddening law, we thus measured $F_{obs}/F_{em}$ and derived $A_V$, both shown in Figure 10. As can be seen, the two extinction measurements agree well both in regard to strength and spatial variation of the extinction. The 1.3 mm continuum map of Downes & Eckart (2007) could give us valuable information about the spatial distribution of the obscuring dust; however, unfortunately only two barely resolved point sources are detected at their sensitivity level. Downes & Eckart (2007) estimate the optical depth for the western nucleus to be $\tau_{opt}(1.3 \text{mm}) \gtrsim 0.7$; adopting their assumptions also for the eastern nucleus, we estimate $\tau_{opt}(1.3 \text{mm}) \gtrsim 0.15$; this is by extension also an upper limit of the off-nuclear $\tau(1.3 \text{mm})$. For $\tau \propto \lambda^{-2}$, $\tau \sim 0.15$ implies that all emission shortward of 500 μm is optically thick. There appear to be two different regimes: the extremely opaque central $\sim 50$ pc which are fully obscured at near-infrared wavelengths ($\tau = 1$ at 500 μm) and the outer parts where we can detect reddened near-IR emission (and where we find $\tau = 1$ is at $\sim 2.5$ μm). This plausibly explains why even after applying the reddening correction, we do not recover all the near-IR luminosity; we are simply not seeing all that is emitted in the central region. We note that this is qualitatively similar to what we found in NGC 6240 (Engel et al. 2010a): over most of the disk the near-infrared obscuration is moderate, but increases dramatically in the central tens of parsecs of each nucleus.

However in the $H$ and $K$ bands, this would only be observable if very hot dust were present. Since any continuum emission due to hot dust would lead to dilution of the CO absorption bandheads, and since we are seeing absorption depths very near the theoretically possible maximum of $\sim 17$ Å, we can exclude the possibility of any significant hot dust emission.
Figure 8. Comparison of different extinction models: we fitted a synthesized stellar population spectrum to HST photometric data points extracted in 0″15 radius apertures in a range of locations across our FOV (four examples shown), by reddening the synthetic spectral energy distribution until it matched the data. Gray: mixed extinction; black: screen extinction; magenta: the Calzetti et al. (2000) reddening law. As can be seen, the Calzetti et al. (2000) reddening law produces the best fit to the data.

(A color version of this figure is available in the online journal.)

Figure 9. Left: $F_{\text{obs}}/F_{\text{em}}$ in the $K$ band, derived by fitting a stellar template to the line-free continuum using the Calzetti et al. (2000) reddening law. Right: corresponding optical extinction $A_V$. Contours trace the continuum.

(A color version of this figure is available in the online journal.)

| Region             | $L_k$ $^a$ | EW CO $^a$ | EW Br$_\gamma$ $^a$ | $L_{K, \text{non-SB}}/L_K$ $^b$ | $L_{\text{bol}}/L_K$ $^b$ | $L_{K, \text{non-SB}}/L_K$ $^c$ | $L_{\text{bol}}/L_K$ $^c$ |
|--------------------|------------|------------|---------------------|---------------------------------|--------------------------|---------------------------------|--------------------------|
| SINFONI FOV        | $3.25 \times 10^8$ $L_\odot$ | 14.78 Å    | 7.09 Å              | 0.13                            | $151 \pm 25$             | 0.44                            | $49 \pm 9$               |
| Western nucleus    | $9.5 \times 10^8$ $L_\odot$   | 15.72 Å    | 8.69 Å              | 0.08                            | $111 \pm 12$            | 0.26                            | $51 \pm 5$               |

**Notes.** Stellar population analysis. We assume the starburst population to have EW CO$_{\odot} =$ 17 Å, as measured between the two nuclei, and calculate the luminosity contribution of a younger (EW CO$_{\odot} = 0$ Å) or older (EW CO$_{\odot} = 12$ Å) stellar population required to dilute the CO absorption bandheads to the measured values. We furthermore calculate the expected $L_{\text{bol}}/L_K$ for each case. The EW Br$_\gamma$ furthermore indicates the presence of a very young ($\lesssim 7$ Myr) stellar population, the luminosity contribution of which, however, at less than a few percent of the total, is negligible.

$^a$ Measured.

$^b$ Assuming the non-starburst population to be $\gtrsim 8$ Myr old with EW CO$_{\odot} =$ 0 Å.

$^c$ Assuming the non-starburst population to be $\lesssim 20$ Myr old with EW CO$_{\odot} =$ 12 Å.

### 4.2. Extinction

The significant reddening quantified in Section 4.1 is indicative of a substantial amount of stellar light emitted in the near-infrared in the central region of Arp 220, which is completely absorbed, and re-emitted at longer wavelengths. Here, we attempt to quantify the amount of “missing light” in the $K$ band, by comparing the infrared luminosity, calculated from IRAS flux measurements, to the stellar bolometric luminosity calculated from our measured $L_K$ and the $L_{\text{bol}}/L_K$ expected from our stellar population analysis (Section 3 and Table 1). We use the Sanders et al. (2003) IRAS fluxes from the Revised Bright Galaxy Sample and calculate the infrared flux via $F_{\text{IR,8–1000 } \mu m} = 1.8 \times 10^{-14} \times (13.48 \times F_{12} + 5.16 \times F_{25} + 2.58 \times F_{60} + F_{100})$ W m$^{-2}$, with $F_{12}$, the IRAS flux density in Jy at 12 $\mu$m, etc. (Sanders & Mirabel 1996). We then convert this to infrared luminosity, $L_{\text{IR}} = 3.127 \times 10^7$ $D^2 F_{\text{IR}} L_\odot$ (D in pc). This yields $L_{\text{IR,8–1000 } \mu m} = 1.37 \times 10^{12} L_\odot$. Nardini et al. (2010) perform a 5–8 $\mu$m spectral analysis of Arp 220 using the Infrared Spectrograph on board Spitzer; they find a 17% AGN contribution to the bolometric luminosity of Arp 220, which we need to correct for in order to find the stellar bolometric luminosity. However, this
is largely offset by the translation of infrared into bolometric luminosity, which for ULIRGs is typically \(L_{\text{bol}} = 1.15 \times L_{\text{IR}}\) (Kim & Sanders 1998). This yields a total stellar bolometric luminosity of \(1.31 \times 10^{12}\) \(L_\odot\). We then measure the K-band luminosity of Arp 220 using the archival HST NICMOS images already utilized in Section 2.1.2, finding \(L_K = (1.75 \pm 0.1) \times 10^{9}\) \(L_\odot\) (for comparison, our SINFONI data yield \(L_K = (1.34 \pm 0.07) \times 10^{9}\) \(L_\odot\) for the SINFONI FOV, implying that \(\sim 80\%\) of the total \(L_K\) are emitted in the nuclear region—cf. Wynn-Williams & Becklin 1993). This results in an \(L_{\text{bol}} / L_K\) of \(\sim 750\), whereas our earlier stellar population analysis (Section 3) requires \(\sim 150\) (theoretically expected for 10 Myr old starburst plus younger stellar population with the derived relative luminosity contributions; cf. Table 1) or \(\sim 50\) (10 Myr old starburst plus older stellar population)—implying that in the K band we are missing a factor of \(\sim 5\) or \(\sim 15\) of light, respectively. As we show in Section 3, the assumption of a population younger than 10 Myr is inconsistent with our dynamical mass estimate, and we can therefore exclude this alternative. We thus conclude that in the K band, we are only observing \(\sim 7\%\) of the actually emitted (no reddening-correction) stellar light. This is consistent with Rodríguez Zaurin et al. (2008), who find that the bolometric luminosity derived from optical wavelength observations is an order of magnitude smaller than the mid- to far-infrared luminosity, and are led to conclude that “most of the ongoing star formation in the nuclear region is hidden by dust.” Further support for our result is lent by the supernova rate estimates of Rovilos et al. (2005); these authors derive the supernova rate \(\sim 0.7\) yr\(^{-1}\) for the western nucleus. STARS predicts a supernova rate of \(10^{10} L_K^{-1}\) yr\(^{-1}\) for a 10 Myr old instantaneous starburst. For our corrected K-band luminosity, of which \(\sim 75\%\) are attributed to the 10 Myr old starburst, a supernova rate of \(\sim 1.0\) yr\(^{-1}\) is implied.

5. WESTERN NUCLEUS

5.1. Stellar and CO(2–1) Kinematics

As Figure 3 shows, the stellar kinematics exhibit a clear rotational signature around the western nucleus. In order to extract a rotation curve and find the kinematic center of the stellar rotation, we fit an inclined disk model to the velocity map (Figure 11). The best-fitting model has an inclination \(q = 0.62 \pm 0.06\) and a position axis (PA hereafter) of \(9.8 \pm 0.4\) deg south of west, with average residuals of 12.2 km s\(^{-1}\). We also derive a dispersion profile by azimuthally averaging the two-dimensional dispersion map. Note that we do not suggest that the stars in the western nucleus are moving in a thin disk—we simply parameterize the rotation field in terms of circular orbits with a fixed center, PA, and inclination, in order to derive a rotation curve and kinematic center.

The CO(2–1) also displays a regular rotation pattern around the western nucleus, which we model analogous to the stellar velocity analysis. The best-fitting model (Figure 12) indicates an inclination \(q \approx 0.56\) and PA \(\approx 3\) deg south of west, with the kinematic center coincident with that of the stellar velocity field within the uncertainties. The stellar and CO(2–1) kinematics in the western nucleus thus seem to agree well.

5.2. Kinematic Center and Hot Dust Emission

Downes & Eckart (2007) detect emission from a hot, compact dust ring just south of the CO(2–1) emission peak of the western

Figure 10. Left: \(F_{\text{obs}} / F_{\text{em}}\) in the K band, derived by comparing the observed flux ratio of Paα and Brγ to the theoretically expected value, again using the Calzetti et al. (2000) reddening law. Right: corresponding optical extinction \(A_V\). Contours trace the continuum.

(A color version of this figure is available in the online journal.)

Figure 11. Western nucleus: stellar velocity field, best-fitting disk model, and residuals. The kinematic center is marked by a black circle, and the major axis is indicated with a white dashed line. 1 pixel corresponds to 0′′05.

(A color version of this figure is available in the online journal.)
nucleus, which they interpret as being heated by an AGN accretion disk. We locate the position of the continuum emission using the relative position of the dust emission peak and the CO(2–1) emission, and assuming that the peak of the stellar continuum in the western nucleus is coincident with that of the CO(2–1) emission (as outlined in Section 2.2). Intriguingly, the putative AGN position thus derived is coincident with the kinematic center of the stellar and CO(2–1) rotation found in Section 5.1. This strongly suggests that the stars in the western nucleus are moving in a gravitational potential with either a supermassive black hole (Downes & Eckart 2007) or an extremely dense, young starburst (Sakamoto et al. 2008) at its center.

5.3. Dynamical Mass Estimate

In principle, our data are of high enough quality to derive the dynamical mass via Jeans modeling. However, as we found in Section 4, Arp 220 is severely affected by extinction in the K band. Since we do not know the relative three-dimensional distribution of the obscuring material, it is impossible to derive the intrinsic kinematics from the observed two-dimensional line-of-sight projections. We therefore have to content ourselves with a simpler estimate of the dynamical mass. We adopt the approach taken by Bender et al. (1992), which is based on the tensor virial theorem (Binney & Tremaine 1987), and refer the reader to Appendix B of Bender et al. (1992) for a detailed discussion. According to this, the appropriate dynamical mass formula for the relative stellar velocities and dispersions of the western nucleus is 

$$M_{\text{dyn}} = 1.12 \times 3 \times \sigma_{\text{L}}^2 \times R / G.$$ 

Using the stellar rotation and dispersion profiles derived in Section 5.1, this yields an enclosed dynamical mass out to ~100 pc (180 pc) of 

$$6.3 \times 10^8 M_\odot. \quad (9.0 \times 10^8 M_\odot).$$

Since the CO data probe significantly deeper than the K-band stellar kinematics, we use these to obtain another mass estimate. We use the code described in Cresci et al. (2009) to model the CO emission as arising from a thick rotating disk, taking beam smearing effects into account. We achieve the best match to the observed flux, velocity, and dispersion maps with a mass distribution in which the majority (>80%) of the mass is concentrated within a radius of ~0.15 (50 pc). An even more concentrated mass distribution (point mass) also gives a good match (although the more extended distribution is preferred)—the 0.3 beam size prevents a definitive differentiation here. The total mass predicted within a radius of 100 pc is 

$$1.6 \times 10^9 M_\odot,$$

although we note that our model underpredicts the central dispersion by ~60 km s⁻¹, and hence this value probably is somewhat too low. Since our modeling cannot definitively exclude a significant mass distribution from a central point mass (i.e., black hole), and since the presence of such a non-luminous mass would have ramifications for our analysis in Section 3, we note here that the black hole mass expected from the \(M_{\text{BH}}-\sigma\) relation of Tremaine et al. (2002) is 

$$1.4 \times 10^9 M_\odot; \quad i.e., \quad \text{less than 10\% of the total dynamical mass.}$$

Downes & Solomon (1998) estimate a gas mass for the western nucleus of 

$$6 \times 10^8 M_\odot, \quad \text{based on 1.3 mm dust emission, implying a gas fraction of \sim 10\%, which agrees well with what is expected for local ULIRGs and starburst galaxies (Hicks et al. 2009 and references therein).}$$

6. EASTERN NUCLEUS

6.1. Stellar and Gas Kinematics

The stellar kinematics of the eastern nucleus are more difficult to interpret; although a strong velocity gradient is clearly present, pinning down a rotational major axis is much less obvious. The CO(2–1) kinematics are even more intriguing; the velocity map appears as a step function, with the velocity changing abruptly from −135 to +205 km s⁻¹. In order to investigate this, and any differences from the western nucleus, we produced P–V diagrams across each nucleus, also mapping the 1.3 mm continuum emission. As can be seen (Figure 13), the P–V diagram of the western nucleus is fairly typical of a rotating disk or spheroid, with only a slight flux gap in velocity space near the center of rotation. The eastern nucleus however appears markedly different, with a gap of almost 200 km s⁻¹ between the two emission regions. To understand this, we construct a model of the eastern nucleus, using the simple ansatz that we are seeing two unresolved sources at different velocities (we note that at this stage we do not make any assumptions about the actual gas distribution, only the actually observed emission—as we discuss below, the gas is in fact mostly likely in a disk, but we can only see emission from two unresolved sources). After convolving a model data cube with the PSF of the CO observations, we extract a flux map and P–V diagram and compare it to the data. As Figure 14 shows, the match achieved is striking—supporting our hypothesis that we are indeed seeing two compact, unresolved emission sources. Moreover, as Figure 13 shows, the peak of the continuum emission lies at the center of rotation, and hence the gravitational potential. We constrain the mass enclosed, by assuming that the two sources are on circular orbits, and calculating the enclosed mass for a range of inclinations of the rotation plane. Excluding the most extreme inclinations (\(q < 0.25\) and \(q > 0.9\)), we derive a dynamical mass of 

$$1.8 \pm 0.5 \times 10^9 M_\odot$$

within 0.22, or 81 pc. However, this must be regarded as a lower limit (unless the gas is in a perfectly thin disk) since it neglects dispersion.

This appears strongly suggestive of a gas disk centered on the continuum emission. However, one might wonder why in this case we are not seeing strong CO(2–1) emission from the
center. There clearly are significant amounts of gas present in the line of sight to the continuum peak—Sakamoto et al. (2009) find the HCO$^+$ emission from the center to display P-Cygni profiles. This, as they elaborate, is indicative of outflowing gas absorbing the continuum emission. We confirm the presence of absorbing gas by noting that the (continuum-subtracted) CO line emission at velocities near systemic appears ring like around the continuum peak (Figure 15)—a clear signature of continuum absorption. It is therefore plausible that colder gas in the line of sight also causes a drop in CO line emission through line self-absorption. This also implies that the geometry of the eastern nucleus is similar to that of the western nucleus, in that there is a very dense, compact obscured central region about 50 pc across which is completely obscured from the far-IR to shorter wavelengths, and that around this there is a smaller, but still significant, mass distributed over a large region with much lower mass surface density, and hence much lower obscuration.

6.2. Dynamical Mass Estimate

As the stellar kinematics of the eastern nucleus do not allow a straightforward measurement of a rotation major axis, we therefore instead use the kinematic center and PA of the CO(2–1) velocity field (Figure 5) to measure the stellar rotational velocity and dispersion at a radius of $\sim$230 pc (100 pc). Analogous to Section 5.3, this yields an enclosed mass of $11.2 \times 10^9 M_\odot$ ($5.8 \times 10^9 M_\odot$). As outlined in Section 6.1, the CO kinematics suggest a lower limit to the dynamical mass of $(1.8 \pm 0.5) \times 10^9 M_\odot$ within 81 pc. We note that this indicates very similar masses for the western and eastern nuclei within 100 pc radius, and, due to the more centrally concentrated distribution, that at smaller radii the enclosed mass of the eastern nucleus is in fact larger than that of the western nucleus. Downes & Solomon (1998) estimate a gas mass of $1.1 \times 10^9 M_\odot$ for the eastern nucleus, again implying a gas fraction of $\sim$10%.

6.3. Nature of Eastern Nucleus

As our data show, different tracers display different morphologies at the eastern nucleus (cf. also the high-resolution Keck maps of Soifer et al. 1999), raising the question whether we are seeing a kinematically coherent structure, or something different (a gas streamer, e.g.). The two-dimensional velocity fields of the CO(2–1) and various $K$-band tracers all appear broadly similar, suggesting that they are all governed by the same gravitational potential. One way to look at this is to directly compare the velocities of the different tracers. Figure 16 plots the velocity of the emission peak of a number of tracers along the CO(2–1) rotation major axis; as can be seen, the velocity differential is largest for CO(2–1), followed by the $K$-band gas tracers, and somewhat smaller still for the stars. Since the two-dimensional velocity fields of these all appear qualitatively broadly similar, these differences are most likely due to the different depths probed by the CO(2–1) and the $K$-band tracers, rather than inherently different three-dimensional velocity structures. The slightly smaller stellar velocities are expected, since rotating gas quickly collapses to a disk, whereas the stars are likely in a more spheroidal distribution, and hence have a larger fraction of their kinetic energy locked up in dispersion, rather than rotation. We therefore conclude that the eastern nucleus, like the western nucleus, is a kinematically coherent structure. This, in conjunction with our stellar population analysis...
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Figure 15. Integrated CO(2–1) flux map, with insets showing the CO line flux from a narrow velocity range near systemic velocity; contours mark mm-continuum emission. As can be seen, in those wavelength intervals, the (continuum-subtracted) line emission drops markedly toward the continuum peaks. This is a clear indication for continuum absorption by the line-emitting gas.

(A color version of this figure is available in the online journal.)

Figure 16. Position and velocities of CO(2–1) and various K-band tracers in the eastern nucleus, along the CO(2–1) rotation major axis. CO(2–1) displays the largest velocity differential, followed by the K-band gas tracers, and finally the stars. This is interpreted as arising due to the different depths probed by the various tracers.

(A color version of this figure is available in the online journal.)

(Section 3), leads to the obvious conclusion that most likely the nuclei are (remnants of) the progenitor galaxies’ bulges.

Since mm-wavelength CO(2–1) observations are significantly less affected by extinction than K-band tracers, and given that our analysis above clearly shows that our CO(2–1) observations are probing deeply into the eastern nucleus, we can use these to assess the depth to which our K-band tracers are probing. We do this by utilizing our model from Section 6.1 again, and making the simplifying assumption that the gas and stars we are observing in the K band are also moving in a (thick) disk structure in the same gravitational potential as the cold gas. From this starting assumption, we then calculate at what distance above the disk midplane the different K-band emitters must be rotating to have velocities as observed. We find that generally they are 0.5–1 times as high above the disk midplane as their radial distance from the rotation axis—implying that we are only probing the outer regions of the eastern nucleus in the K band, in agreement with the large extinction we found earlier (Section 4).

Figure 17 shows the extinction map, with the emission peaks of the various tracers, and the regions of high EW_{Brγ} (>16 Å, black) and EW_{CO} (>16 Å, white) which indicate regions with large flux contributions from recent star formation. As can be seen, both the region with lots of recent star formation and the region with high extinction are elongated along the major axis of the CO(2–1) rotation, but offset from each other, with one on either side of the major axis. This suggests that we are seeing a thick disk/spheroid embedded in the larger scale gas disk, with the northwestern half in front, and the southeastern half behind the gas disk, leading to the offset regions of high extinction (lower half of nucleus obscured by gas disk) and high star formation (nucleus above disk plane). We have indicated the suggested outline of the nucleus in Figure 17. We note that this is supported by Figure 8 of Sakamoto et al. (2008), which shows the location of the radio supernovae/supernova remnants (Parra et al. 2007) in relation to the 860 μm continuum emission.

7. NUCLEI AND LARGE-SCALE GAS DISK

Scoville et al. (1997), Downes & Solomon (1998), and Mundell et al. (2001) show that the two nuclei are embedded in a larger scale gas disk, with an estimated gas mass of $\sim 3 \times 10^9 M_\odot$ (Downes & Solomon 1998). Our observations are consistent with this; the H$_2$ kinematics clearly show rotational motion across the full SINFONI FOV (Figure 4).

As outlined in Sections 5 and 6, the western nucleus is quite compact, whereas the eastern nucleus appears more extended. Scoville et al. (1998) propose that the crescent-like K-band continuum morphology of the western nucleus is due to an embedded opaque dust disk, which absorbs the stellar light from the southern half of the nucleus (their Figure 6). This is supported by the stellar velocity map presented here (Figure 3), which shows that the stellar rotation field is regular and extends to the supposedly extincted lower half. The embedded dust disk appears limited in extent, since in the Scoville et al. (1998) NICMOS data, emission from the southernmost tip of the western nucleus is visible. Turning to the eastern nucleus, as we argue in Section 6.3, the extinction pattern and EW_{CO} suggest that here we are seeing a more extended spheroid, the southeastern half of which is more strongly reddened due to being embedded in the larger scale gas disk. While confirming the general picture put forward by Mundell et al. (2001, cf. their Figure 7), in which the eastern nucleus is coplanar with the main
major axis. This suggests that we are seeing a thick disk of the CO(2–1) rotation, but offset from each other, with one on either side of the formation and the region with high extinction are elongated along the major axis from recent star formation. As can be seen, both the region with lots of recent star ULIRG Arp 220. Our main conclusions are the following.

5. The eastern nucleus displays a markedly different morphology. Two emission peaks are seen in CO(2–1). We model the CO(2–1) data as two unresolved sources orbiting around the center of the continuum emission; this produces an excellent match. We find a clear signature for continuum absorption by the CO line-emitting gas; it is plausible that self-absorption also leads to the curious CO(2–1) morphology. Comparison of the velocities of the mm and K-band tracers shows that CO(2–1) has a larger velocity gradient, which is expected since mm observations probe deeper into the obscured nucleus. We therefore conclude that the eastern nucleus is also a coherent structure, albeit more extended than the western nucleus. This, in conjunction with our stellar population analysis, strongly suggests that the nuclei are (remnants of) the progenitors’ bulges.

6. This indicates that both nuclei have a similar structure in that there is a very dense and massive, but compact, structure in the central ∼50 pc which is almost completely obscured at wavelengths shorter than far-IR, and around this is a more extended component with much lower mass surface density and lower extinction, but which is responsible for most of the observed luminosity. In general, we agree with the geometry suggested by Mundell et al. (2001), and can refine it further. Comparison of the extinction map, EW CO, with EW Brγ suggests that the lower half of the eastern nucleus is much more obscured than the upper half. This can plausibly be explained if the eastern nucleus is coplanar with the larger scale gas disk and its lower half is buried in, and hence observed through, this gas disk. The very similar systemic velocities of the two nuclei and the nearly face-on orientation of the large-scale gas disk suggest that the merger plane is approximately face-on.

8. CONCLUSIONS AND SUMMARY

We present new adaptive optics integral field spectroscopy near-infrared data and reanalyze interferometric mm CO(2–1) and continuum emission observations of the prototypical ULIRG Arp 220. Our main conclusions are the following.

1. We show that in the central kpc, a 10 Myr old starburst provides the majority of the K-band luminosity, with a ≥1 Gyr old stellar population accounting for the remainder of the luminosity and accounting for much of the mass. There is also a small contribution by stars ≤8 Myr old, which are responsible for the Brγ emission.

2. The Calzetti et al. (2000) reddening law is found to provide the best fit to photometric data points spanning 0.45 μm to 2.12 μm.

3. Estimating the system’s bolometric luminosity from IRAS fluxes, we find that we only see ∼7% of the observed (non-reddening corrected) K-band luminosity. Since a reddening correction would only increase the observed flux by a factor of ~2–3, this implies that there is a significant amount of emitted K-band light which is completely obscured.

4. Assuming that the CO(2–1) emission and the K-band continuum peaks of the western nucleus coincide, we find

that the stellar kinematic center is coincident with the mm continuum emission peak. This indicates that the mm continuum emission marks the center of the gravitational potential in which the stars and gas are moving. The CO(2–1) and the stellar kinematics agree well, and all the K-band tracers peak at the same position; this indicates that the western nucleus is a compact, coherent structure.

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CO disk, and the western nucleus lies above it, we have shown that the eastern nucleus is half embedded in the main CO disk. Furthermore, as our CO and stellar kinematics maps show, the relative velocities of the two disks are nearly identical. This, and the roughly face-on orientation of the large-scale gas disk, suggests that the merger is taking place roughly in the plane of the sky.
