The State of the Molecular Gas in Post-starburst Galaxies

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Abstract

The molecular gas in galaxies traces both the fuel for star formation and the processes that can enhance or suppress star formation. Observations of the molecular gas state can thus point to when and why galaxies stop forming stars. In this study, we present Atacama Large Millimeter/submillimeter Array observations of the molecular gas in galaxies evolving through the post-starburst phase. These galaxies have low current star formation rates (SFRs), regardless of the SFR tracer used, with recent starbursts ending within the last 600 Myr. We present CO (3–2) observations for three post-starburst galaxies, and dense gas HCN/HCO+/HNC (1–0) observations for four (new) post-starburst galaxies. The post-starburst galaxies have low excitation traced by the CO spectral-line energy distribution up to CO (3–2), more similar to early-type than starburst galaxies. The low excitation indicates that lower density rather than high temperatures may suppress star formation during the post-starburst phase. One galaxy displays a blueshifted outflow traced by CO (3–2). MaNGA observations show that the ionized gas velocity is disturbed relative to the stellar velocity field, with a blueshifted component aligned with the molecular gas outflow, suggestive of a multiphase outflow. Low ratios of HCO+/CO, indicating low fractions of dense molecular gas relative to the total molecular gas, are seen throughout post-starburst phase, except for the youngest post-starburst galaxy considered here. These observations indicate that the impact of any feedback or quenching processes may be limited to low excitation and weak outflows in the cold molecular gas during the post-starburst phase.

Unified Astronomy Thesaurus concepts: E+A galaxies (424); Post-starburst galaxies (2176); Galaxies (573);
Molecular gas (1073)

1. Introduction

Multiwavelength observations of galaxies across cosmic time are revealing a detailed picture of how galaxies grow, evolve, and ultimately become quiescent. While some galaxies in the local universe have gradually ended star formation over many billions of years, others show signs of a sudden end to star formation, having undergone rapid evolution from starbursting to quiescent (e.g., Schawinski et al. 2014). Such post-starburst galaxies display substantial populations of young A-type stars, yet little emission-line flux from H II regions around O- or B-type stars, indicating a recent starburst that has since ended (Dressler & Gunn 1983; Couch & Sharples 1987). Post-starburst galaxies provide evidence for fast evolution, likely driven by recent mergers (Zabludoff et al. 1996; Pawlik et al. 2015; Sazonova et al. 2021). At higher redshifts, large fractions of quiescent galaxies show signs of being post-starburst, suggesting that this process of rapid evolution is more common (Wild et al. 2009; Snyder et al. 2011; Whitaker et al. 2012; Wild et al. 2016; Rowlands et al. 2018; Belli et al. 2019; Wild et al. 2020; D’Eugenio et al. 2020). In order to match the high-mass, quiescent end of the galaxy population, simulations must add in feedback from active galactic nuclei (AGNs) to limit and ultimately end star formation (e.g., Di Matteo et al. 2005; Croton et al. 2006). Yet the process of how and if AGN feedback operates in its different regimes across galaxy type, and the contribution of stellar feedback, is not well understood.

Galaxies evolving through the post-starburst phase are laboratories for understanding how and when star formation ends, the role of feedback processes, and the connection between the evolution of galaxies and their supermassive black holes (see French 2021 for a recent review). In order to understand the changes in star formation, we must look to the molecular gas properties of evolving galaxies to study the potential fuel for that star formation. Previous work has uncovered high molecular gas fractions traced by CO (1–0) single-dish observations in multiple samples of post-starburst galaxies at z ∼ 0.1 (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016), contrary to expectations that these galaxies would already be devoid of gas.

The observation of large CO-traced molecular gas reservoirs remaining in post-starburst galaxies raises the question of why they have become quiescent and what prevents the CO-traced molecular gas from forming stars. If large gas reservoirs exist but are in a relatively diffuse state, this would explain why star formation is no longer occurring at high rates. In previous
work, we presented the nondetection of dense gas tracers in two post-starburst galaxies, with upper limits consistent with the low star formation rates (SFRs) of these galaxies, indicating that these galaxies have stopped forming stars due to a lack of dense gas (French et al. 2018a). This absence of detected dense gas raises the new question of what physical properties in the diffuse molecular gas are preventing its collapse into forming stars. Is the gas heated? Is it kinematically disturbed? Is there evidence of energy injection from AGNs? In order to address these questions, we require detections (rather than limits) of the dense gas tracers in post-starburst galaxies.

In this work, we aim to explore the molecular gas state of post-starburst galaxies by studying their CO excitation and by using multiple tracers of the dense molecular gas from observations with the Atacama Large Millimeter/submillimeter Array (ALMA). We present observations of CO (3–2) for three post-starburst galaxies with previous CO (1–0) and (2–1) observations, as well as observations of dense gas tracers HCN (1–0), HCO$^+$ (1–0), and HNC (1–0) for four new post-starburst galaxies, which we combine with the previous sample of two measurements from French et al. (2018b). When needed, we assume a flat cosmology with $h = 0.7$ and $\Omega_m = 0.3$.

### 2. Observations

#### 2.1. Sample Selection

Our targets are selected from two parent samples of post-starburst galaxies with previous molecular gas detections, both of which were originally selected using Sloan Digital Sky Survey (SDSS) spectroscopy. Galaxies from French et al. (2015) and Smercina et al. (2018) are selected to have low H$\alpha$ emission (H$\alpha$ equivalent width $<$3 Å in emission) and strong Balmer absorption (Lick H$\delta_A$ at least 1σ above 4 Å; H$\delta_A - \sigma(H\delta_A)$ > 4). Galaxies from Rowlands et al. (2015) were selected using a principal component analysis (PCA) from Wild et al. (2007, 2009). These PCA components correspond roughly to $D_{sl}4000$ and H$\delta$. The PCA-selected post-starburst galaxies identify galaxies earlier in the post-starburst phase and with higher SFRs than post-starburst galaxies selected using a cut against H$\alpha$ emission (Wild et al. 2009; French et al. 2018a).

We summarize our targets, their coordinates and redshifts, post-burst ages from French et al. (2018a), and ALMA data set numbers in Table 1. We select our samples from previous studies of CO-traced molecular gas in post-starburst galaxies. We select two samples of galaxies for observing CO (3–2) (rest frame $\nu = 345.7960$ GHz) in ALMA Band 7 and for observing HCN (1–0) (hydrogen cyanide; rest frame $\nu = 88.6316$ GHz), HCO$^+$ (1–0) (formyl; rest frame $\nu = 89.1885$ GHz), and HNC (1–0) (hydrogen isocyanide; rest frame $\nu = 90.6636$ GHz) in ALMA Band 3. The CO (3–2) sample is a subset of the HCN/HCO$^+$/HNC sample.

| Galaxy | R.A. (deg) | Decl. (deg) | $z$ | Post-burst Age (Myr) | HCN/HCO$^+$/HNC Data set | CO (3–2) Data set |
|--------|------------|-------------|-----|---------------------|--------------------------|------------------|
| H02    | 141.580    | 18.6781     | 0.0541 | 201   | (2016.1.00881; (1)) | 2017.1.00930     |
| H03    | 222.067    | 17.5517     | 0.0449 | 381   | 2017.1.00930       |                  |
| S02    | 49.2288    | –0.0420     | 0.0231 | 522   | 2017.1.00930       |                  |
| S05    | 146.112    | 4.49912     | 0.0467 | 259   | (2016.1.00881; (1)) |                  |
| R02    | 228.951    | 20.0224     | 0.0363 | –4    | 2018.1.00948       |                  |
| R05    | 244.398    | 14.0523     | 0.0338 | 10    | 2018.1.00948       |                  |

Note. Names match those in French et al. (2015), Smercina et al. (2018), French et al. (2018b), and Smercina et al. (2022). Galaxy coordinates and redshifts are from the SDSS main spectroscopic survey (Strauss et al. 2002). Post-burst ages measure the time since the starburst ended, taken from French et al. (2018a). Galaxies with negative ages are those where the best-fit model is a still-declining burst.

Reference. (1) French et al. (2018b).

#### 2.2. Atacama Large Millimeter/submillimeter Array Observations

Observations of CO (3–2) for three post-starburst galaxies were taken during Cycle 5 (program 2017.1.00930; PI: French). We use the Band 7 receiver and place the redshifted CO (3–2) line in a 1875 MHz wide spectral window with 3840 channels of width 1129 KHz. This corresponds to roughly 1700 km s$^{-1}$ with channels of width 1 km s$^{-1}$ for our objects. The requested spatial resolution was chosen to be $\sim0.7$, in order to obtain $\sim9$ resolution elements per galaxy, assuming the galaxies had similar size to the CO (2–1) measurements of a partially overlapping sample from Smercina et al. (2022). The data were pipeline calibrated using the CASA pipelines indicated in Table 2. Briggs weighting was used with the

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**Table 1: Post-burst Galaxy Targets**

| Galaxy | R.A. (deg) | Decl. (deg) | $z$ | Post-burst Age (Myr) | HCN/HCO$^+$/HNC Data set | CO (3–2) Data set |
|--------|------------|-------------|-----|---------------------|--------------------------|------------------|
| H02    | 141.580    | 18.6781     | 0.0541 | 201   | (2016.1.00881; (1)) | 2017.1.00930     |
| H03    | 222.067    | 17.5517     | 0.0449 | 381   | 2017.1.00930       |                  |
| S02    | 49.2288    | –0.0420     | 0.0231 | 522   | 2017.1.00930       |                  |
| S05    | 146.112    | 4.49912     | 0.0467 | 259   | (2016.1.00881; (1)) |                  |
| R02    | 228.951    | 20.0224     | 0.0363 | –4    | 2018.1.00948       |                  |
| R05    | 244.398    | 14.0523     | 0.0338 | 10    | 2018.1.00948       |                  |
robustness values chosen to best match the requested beam size and sensitivity.

Observations of several dense gas tracers were taken of four post-starburst galaxies during cycles 5 and 6 (programs 2017.1.00935 and 2018.1.00948; PI: French). We use the Band 3 receiver and three spectral windows to observe HCN (1–0), HCO⁺ (1–0), and HNC (1–0). We use wide spectral windows (≈1600–6600 km s⁻¹), depending on the closeness of the lines to the edges of the Band 3 frequency range, and channel widths ~2 km s⁻¹. The requested spatial resolution was chosen to be 1″, in order to match the total spatial extent of the dense gas emission estimated from CO (2–1) observations (Smercina et al. 2022) and dense gas observations in luminous infrared galaxies (LIRGs). This resolution scale is larger than the typical size of dense-gas-emitting clumps, which we do not expect to measure individually. The data were pipeline calibrated using the CASA pipelines indicated in Table 2. Imaging parameters were chosen to best match the requested sensitivity and beam size. For the cases in which no lines are detected (HNC in R05 and all lines in S02), we manually reimaged the data using updated continuum regions and natural weighting (robustness = 2), but are unable to detect any additional emission. We also reimaged these data sets using a UV taper of 3″ and are still unable to detect any additional emission. Two of the data sets (H03 and R02) were manually reimaged by the ALMA pipeline scientists to refine the continuum subtraction.

Moment maps and extracted spectra for both data sets are shown in Appendix A. We extract spectra from a 1.5″ radius centered on the moment 0 map centroid. We integrate the flux density between ±3σgauss from the CO (1–0) line measurements in French et al. (2015) and Rowlands et al. (2015). The continuum regions outside of the line regions are used to determine the uncertainty on the flux measurements. The integrated line fluxes are shown in Table 3. In cases where the signal-to-noise ratio (S/N) is less than 3, we provide a 3σ upper limit on the possible line flux.

2.3. Archival Data

We use Hα-based star formation rates (SFRs) for the post-starburst galaxies from French et al. (2015) and Rowlands et al. (2015) as these measurements are the least biased and most available SFRs for our post-starburst sample. The Hα fluxes are from the SDSS (Strauss et al. 2002) MPA-JHU galSpec catalogs (Brinchmann et al. 2004; Tremonti et al. 2004), and have been corrected for extinction using the Balmer decrement. For the two Rowlands et al. (2015) galaxies (R02, R05), the SFRs are additionally corrected for the contribution from AGN contamination using the method from Wild et al. (2010), as these galaxies were selected without a cut against significant Hα emission (see Section 2.1). We correct for aperture bias using the galSpec SFR aperture bias corrections, which use photometry outside of the fiber aperture to estimate the required correction (Salim et al. 2007), and range from 3.5 to 6.3× corrections for the galaxies considered here. The impact of using different SFR indicators is discussed in Section 4.1. For the sample of post-starburst galaxies with both Hα observations and Spitzer [Ne II] 12.8 μm and [Ne III] 15.6 μm observations, we find no evidence that the Hα observations are missing star formation due to dust obscuration. If there was significant dust obscuration for this sample, we would expect to see neon-based SFRs systematically above the Hα-based SFRs. Instead, we see no systematic shift between the two tracers. Thus, we use Hα-based SFRs throughout the main body of this work, and present the results if IR tracers are used in Appendix B.

3. Results

3.1. Gas Excitation

Observations of multiple J CO lines trace the excitation of the molecular gas; the shape of the CO spectral-line energy density (SLED) depends on the density, kinetic temperature, and observed column density of the gas (Weiß et al. 2007; Carilli & Walter 2013; Narayanan & Krumholz 2014; Bournaud et al. 2015; Kamenetzky et al. 2018). We combine the CO (3–2) measurements of three post-starburst galaxies from this survey with CO (2–1) and CO (1–0) measurements from the IRAM 30 m from French et al. (2015). Resolved studies of CO (2–1) with ALMA of a subset of these galaxies from Smercina et al. (2022) show that the molecular gas in post-starburst galaxies is compact, on ≲1″ scales, such that the ALMA observations are not resolving out extended flux and the single-dish measurements are comparable to the ALMA measurements. We compare the ALMA CO(2–1) flux measurements from Smercina et al. (2022) to the IRAM 30 m
measurements from French et al. (2015) to estimate the uncertainties introduced from combining the measurements. For H02 and H03, the ALMA and IRAM CO (2–1) measurements differ by ~37% (consistent within 1.5σ of the combined uncertainty). For H02, the IRAM flux is larger than the ALMA flux; for H03 the ALMA flux is larger than the IRAM flux. We do not have ALMA CO (2–1) measurements for S02, so we assume it will have a similar uncertainty. These error bars are reflected in Figure 1.

We compare the CO spectral-line energy densities (CO SLEDs) of the three post-starburst galaxies with CO (3–2) measurements of other galaxy samples in Figure 1. The post-starburst galaxies have low CO excitation, consistent with the population of early-type galaxies (Crocker et al. 2012; Bayet et al. 2013), slightly below the population of star-forming galaxies (Leroy et al. 2022), and below most of the LIRGs (Papadopoulos et al. 2012). Even considering the uncertainties from combining ALMA and IRAM measurements, the post-starburst galaxies have low excitation.

Observations of CO (1–0) and CO (2–1) in post-starburst galaxies show low star formation efficiencies (SFEs), SFE ∝ SFR/L CO (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016; Smercina et al. 2018, 2022). The excitation of the CO-traced gas can be used to distinguish between two possible mechanisms that could suppress star formation in the molecular gas, leading to these low SFEs. The first possibility is high kinetic temperatures in the gas paired with low gas densities; in this case, we would expect to see high gas excitation throughout the post-starburst phase. High excitation could also arise from both high temperatures and high densities like those in starburst galaxies, but we would expect to see starburst-like SFRs if the densities were also high. The second possibility for why the post-starburst galaxies have low SFEs is if the gas densities are low. In this case, we would expect to see low gas excitation, similar to early-type galaxies, throughout the post-starburst phase. The observations of the post-starburst excitation presented here favor the second possibility, that the post-starburst galaxies have low densities and temperatures. The low density may explain the low SFEs.

We explore these possibilities more quantitatively by modeling the CO SLEDs with RADEX (van der Tak et al. 2007). RADEX is a non-local thermodynamic equilibrium (non-LTE) code that solves for the radiative transfer of a given molecular species assuming a geometry. Here, we assume a uniform sphere geometry. We use a grid of logarithmically spaced values in temperature (T; 10–300 K), density (n; 104–107 cm−3), and column density of CO (N; 1013–1021 cm−2), similar to that used by Krips et al. (2011). We generate the expected flux ratios of the CO (1–0), CO (2–1), and CO (3–2) lines for this grid of parameters and compare them to the observed line ratios.

The inferred density and temperature values are highly degenerate unless the full rise and turnover of the CO SLED...
can be sampled (e.g., Carilli & Walter 2013; Kamenetzky et al. 2018). We visualize these degeneracies by plotting the likelihoods for the temperature, density, and column density of each source in Figure 2. Densities of $n \sim 3.4$–$3.8$ cm$^{-3}$ and temperatures of $T \sim 15$–$30$ K are favored, although clear degeneracies can be seen between the cases of low density with relatively unconstrained temperature and higher density with low temperature. These values are similar to molecular gas densities and temperatures in early-type galaxies (Bayet et al. 2013), which have densities of $n \sim 3$–$4$ cm$^{-3}$ and temperatures of $T \sim 10$–$70$ K. The post-starburst galaxies have both temperatures and densities less than typical LIRGs. LIRGs have a wide range of densities $n \sim 2.5$–$6.5$ cm$^{-3}$ and temperatures $T \sim 30$–$120$ K (e.g., Greve et al. 2009; Papadopoulos et al. 2012).

We perform additional RADEX modeling of the dense gas tracers HCN (1–0) and HCO$^+$ (1–0) in addition to the CO lines. This analysis is complicated by the need to assume an abundance ratio of either [HCO$^+/CO]$ or [HCN/CO]. For both dense gas tracers, we assume an abundance ratio with respect to CO of $10^{-4}$ (consistent with the range of measurements by Krips et al. 2008 and Aalto et al. 2012). Due to the uncertainties in what is affecting the HCO$^+/HCN$ ratio (Section 3.6), we consider each dense gas tracer individually. In Figure 3, we show the parameter likelihood corner plots considering CO (1–0), CO (2–1), CO (3–2), and either HCO$^+$ (1–0) or HCN (1–0) for the two post-starburst galaxies (H03, S02) with both data sets. For S02, neither dense gas tracer is detected, so we assume the dense gas flux ratios are just below the detection threshold. When the HCO$^+$ constraints are included, the best-fit densities are similar, with sharp cutoffs in likelihood above $n \sim 4$, the effective excitation density of the dense gas tracers (Shirley 2015). The cold molecular gas temperatures indicated by the low CO excitation do not preclude the existence of an additional

12 This assumption only affects the results shown in Figure 3; the results in Figure 2 are independent, as are the results described in subsequent sections.
component of warm or hot gas, as the low J CO lines cannot predict the full SLED in the event of a secondary component of high-temperature molecular gas. In our RADEX analysis, we have assumed the molecular gas is composed of a single-temperature component. However, studies of star-forming and starburst galaxies (e.g., Valentino et al. 2020) have found evidence for multiple components using higher J CO lines than available here. A secondary component of high-excitation molecular gas was also found for NGC 1266 by Pellegrini et al. (2013), better fit by shock models than photon-dominated region (PDR) models. The post-starburst galaxies considered here may also have multiple components of molecular gas, which would require additional CO lines to uncover and may have different filling fractions. Indeed, we expect that such a component exists, as traced by mid-IR H2 rotational lines (Smercina et al. 2018). The extremely high H2/total IR (TIR) ratios observed by Smercina et al. (2018) are indicative of shocks heating a portion of the molecular gas to high temperatures, with a “high-soft” radiation field affecting the dust. By modeling the mass of H2 using the mid-IR warm H2 lines (Togi & Smith 2016) and extrapolating down in temperature to the low-temperature regime probed by the J ≤ 3 CO lines, Smercina et al. (2018) find gas masses typically within a factor of 2–4 times the mass of cold gas inferred from CO (1–0). The higher temperature gas traced by the mid-IR lines comprises a relatively small fraction of the overall mass. By combining these observations, we conclude that the bulk of the gas by mass remains at temperatures lower than typical LIRGs, while a fraction of the molecular gas is highly excited.

We compare the CO (3–2)/CO (1–0) intensity ratio as a tracer of the molecular gas temperature to the mean interstellar radiation field (ISRF) intensity 〈U〉 calculated from dust spectral energy distributions (SEDs) in Figure 4. The 〈U〉 is closely coupled to the dust temperature. Smercina et al. (2018) used Draine & Li (2007) models to fit the IR SEDs of post-starburst galaxies, including the galaxies considered here. We
3.2. Spatially Resolved and Velocity Resolved Observations

We construct zeroth-, first-, and second-order moment maps for the three post-starburst galaxies with CO (3–2) observations, presented in Appendix A. The CO (3–2) emission for each of the three post-starburst galaxies observed has limited extent relative to the optical emission, consistent with the CO (2–1) results from Smercina et al. (2022), which assume a two-dimensional Gaussian profile. The half-light radius of the CO (3–2) emission for each galaxy is shown in Table 4. The sizes range from 0′′38 to 0′′57c, or 367–400 pc. On average, the CO (3–2) sizes are 6.3× smaller than the r-band sizes from the SDSS imaging. Two galaxies (H02 and H03) have both CO (3–2) and CO (2–1) observations; these galaxies have sizes consistent between the two tracers, although differences would be difficult to determine with these observations, as >50% of the flux is contained within a central unresolved beam size in both tracers for both galaxies. The velocity and velocity dispersion maps are broadly consistent, as well. The galaxy S02 has archival MaNGA (Bundy et al. 2015) integral field unit (IFU) data. In Figure 5, we compare the CO (3–2) emission to the post-starburst region with high Hα absorption. Even with the coarser ~2″5 resolution of MaNGA, the post-starburst region with strong Hα absorption is resolved and extends over most of the half-light ellipse of the galaxy. The molecular gas is smaller than the extent of the young stellar population traced by the Hα index.

The small CO (3–2) and CO (2–1) sizes imply very high surface densities of molecular gas and residual star formation. Because of the consistency in sizes between the CO (3–2) measurements here and the CO (2–1) sizes measured by Smercina et al. (2022), we assume these sizes in calculating the molecular gas surface density, \( \Sigma_{H_2} \), from the CO (1–0) luminosities from French et al. (2015). Using the half-light sizes, we calculate the densities as

\[
\Sigma_{H_2} = 0.5 \frac{M_{H_2}}{\pi R_{50}^2},
\]

\[
\Sigma_{SFR} = 0.5 \frac{SFR}{\pi R_{50}^2}.
\]

We compare our observations to the samples of star-forming galaxies from de los Reyes & Kennicutt (2019) and starbursting galaxies from Kennicutt & De Los Reyes (2021) in Figure 6. This set of comparison galaxies is low redshift and covers a similar stellar mass range to the post-starburst galaxies presented here. While the comparison galaxies are on average...
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Figure 6. Molecular gas surface density vs. SFR surface density for post-starburst galaxies from this work with CO (3–2) sizes and from Smercina et al. (2022) with CO (2–1) sizes, as well as comparison samples of star-forming galaxies from de los Reyes & Kennicutt (2019) and starbursting galaxies from Kennicutt & De Los Reyes (2021). The best-fit relation from Kennicutt & De Los Reyes (2021) for the total gas density vs. star formation density is plotted in gray, with a dotted line indicating a factor of 10 below the relation. The post-starburst galaxies have very high molecular gas surface densities, yet they lie below the comparison galaxies, with low SFR surface densities for their molecular gas surface densities. The post-starburst galaxies have SFR surface densities 5.5 below the median for the comparison samples (17 lower than the starburst sample alone). We find qualitatively similar results when using other SFR tracers; see Appendix B and Figure 22.
We fit a series of tilted three-dimensional ring models to S02 using Barolo (Di Teodoro & Fraternali 2015) to model the kinematics of the molecular gas. The position–velocity diagram of the data and best-fit model are shown in Figure 8. The best-fit kinematic major axis of the molecular gas is consistent with that of the stellar velocity. In the position–velocity diagram, the excess flux in the most blueshifted component at \( \sim 100 \text{ km s}^{-1} \) can be seen, inconsistent with the model. This component can also be seen in the asymmetric double peak of the integrated spectrum shown in Figure 20.

We compare the CO (3–2) observations for S02 with archival Hubble Space Telescope (HST) imaging (ID 11643; PI: Zabludoff) and MaNGA (Bundy et al. 2015) IFU data in Figure 9. The stellar velocity field from MaNGA is aligned with the bulk of the molecular gas velocity. The southeastern component is blueshifted with respect to the surrounding stellar velocity field, indicative of an outflowing component. The ionized gas traced by the optical emission lines is disturbed in morphology with respect to the stellar velocity, with the ionized gas blueshifted by \( \sim 40 \text{ km s}^{-1} \) relative to the stellar velocity field. The ionized gas velocity can be measured with good S/N, with a median S/N = 4 over the entire MaNGA field of view, and a S/N = 15–20 over the blueshifted

\[ \text{Figure 7. CO (3–2) channel maps for S02, grouped by velocity bin (blue contours). Each image is 4'' \times 4''. In grayscale, the full moment 0 map is shown for reference. A blueshifted outflow is seen to the lower left of the galaxy at velocities } \sim 64–108 \text{ km s}^{-1}, \text{ in the bottom row of this figure. This component is roughly in line with the rotational axis of the gas in the rest of the galaxy (and the stellar velocity observed from MaNGA observations). The velocity range shown here is symmetric, and yet only a blueshifted outflow is seen without a redshifted counterpart.} \[ \text{Figure 9. The stellar velocity field from MaNGA is aligned with the bulk of the molecular gas velocity. The southeastern component is blueshifted with respect to the surrounding stellar velocity field, indicative of an outflowing component. The ionized gas traced by the optical emission lines is disturbed in morphology with respect to the stellar velocity, with the ionized gas blueshifted by } \sim 40 \text{ km s}^{-1} \text{ relative to the stellar velocity field. The ionized gas velocity can be measured with good S/N, with a median S/N = 4 over the entire MaNGA field of view, and a S/N = 15–20 over the blueshifted} \]
component. The blueshifted CO component is aligned with the blueshifted ionized gas region, indicating a multiphase (both ionized and molecular gas) outflow. When we compare the location of this component to the HST image, it is aligned with a dust lane. It is unlikely that the dust lane is the source of the abnormal ionized gas velocity field due to extinction effects, as the blueshifted ionized gas component extends several arcseconds outside of the dust lane. Instead, the dust may be tracing the outflow similar to the case seen in the post-starburst galaxy IC 860 by Luo et al. (2022). Luo et al. (2022) observe a neutral gas outflow traced by NaD that aligns with a dust feature, with tentative evidence for a molecular gas outflow, consistent with the correlation of dust extinction and neutral gas outflows observed for AGNs (Veilleux et al. 2005).

Thus, while the blueshifted component is aligned with the stellar velocity field and bulk rotation of the molecular gas, it is more likely to be an outflow than an extension of the molecular gas rotation due to (1) the spatially distinct morphology of the outflow (see Figure 7), (2) the asymmetric nature and lack of a counterpart on the northwest side, as evidenced by the excess flux above the best-fit Barolo model (see Figure 8), and (3) the velocity excess over the surrounding stellar velocity field (see Figure 9). The blueshifted component is unlikely to be a parcel of infalling gas from the recent merger, as the smooth stellar velocity field suggests any merger components have already coalesced. In gas-rich, early-type galaxies that have experienced a recent minor merger, position–velocity diagrams do not display as significant asymmetric components as seen here (van de Voort et al. 2018), meaning a merger where the stellar field has coalesced more quickly than the molecular gas is unlikely.

We consider the bulk properties of this component, assuming a distance from the center of the galaxy of $1''$ (460 pc) and a velocity of 100 km s$^{-1}$, based on the blueshifted component’s position in the channel map and position–velocity diagram. If this component is an outflow, its characteristic timescale $\tau$ is 4.5 Myr. The southeast component consists of $\sim 15\%$ of the total flux. Scaling the CO (1–0) inferred molecular gas mass from French et al. (2015) by 15%, the expected mass in this outflowing component is $7.3 \times 10^7 M_\odot$, and the average outflow rate over the timescale of the outflow is $16 M_\odot$ yr$^{-1}$. This is consistent with the (large) range of typical molecular gas depletion rates inferred for the combined post-starburst population by French et al. (2018a). The mass traced by the molecular outflow will dominate over the mass in the ionized gas component, as ionized gas outflow rates are typically low, $\sim 10^{-2} M_\odot$ yr$^{-1}$ (Baron & Netzer 2019).

In order to determine the likely fate of this outflowing gas, we compare the outflow velocity to the escape velocity at its radius of $1''$ (460 pc). We use the stellar mass from the SDSS (Strauss et al. 2002; Brinchmann et al. 2004; Tremonti et al. 2004) and the HST F625W observations to estimate the stellar mass profile of the galaxy. The fraction of stellar mass within the central $1''$ is 0.17, which we use to scale the total mass from SDSS. The estimated stellar mass within this radius is $M_* = 2.04 \times 10^8 M_\odot$. The escape velocity is thus 195 km s$^{-1}$. The outflow velocity of $\sim 100$ km s$^{-1}$ is less than the escape velocity but, given inclination effects, if the angle of the outflow from our line of sight is $\geq 60^\circ$, may exceed the escape velocity from the center of the galaxy.

The inferred outflow kinetic power using $P = \frac{1}{2} M_{\text{outflow}} v^2 / \tau$ is $8 \times 10^{40}$ erg s$^{-1}$. The molecular outflow is comparable to those in star-forming galaxies and low-ionization nuclear emission-line regions (LINERs), and has less kinetic power than those in luminous AGNs (Cicone et al. 2014). Another source of energy may be tidal disruption events (TDEs), which cause a higher rate in post-starburst galaxies than normal galaxies (French et al. 2016, 2020). As in Smercina et al. (2022), we consider the energy input of $\sim 10^{51} - 10^{53}$ erg per TDE (Mockler & Ramirez-Ruiz 2021) and a typical TDE rate of $10^{-3}$ per year per post-starburst galaxy (French et al. 2016), resulting in a total energy source of $\sim 3 \times 10^{40} - 42$ erg s$^{-1}$. The feasibility for energy driving this outflow to come from intermittent AGN/LINER activity or from TDEs will depend heavily on the coupling of energy from the AGN/LINER or TDE to the molecular gas in these galaxies.

The MaNGA data for this source also allow us to investigate the nature of the LINER-like emission seen in the SDSS spectrum. Using the MaNGA data to construct a resolved Baldwin–Phillips–Telervich (BPT; Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003) diagram, most of the galaxy has low emission-line fluxes such that the classification is ambiguous but the spaxels that can be classified are in the LINER part of the BPT diagram (Figure 10). This LINER-like signature extends outside of the nucleus over $\sim 5''$ (10 spaxels), significantly more than the 2$''$ FWHM of MaNGA’s spatial resolution (Law et al. 2016). It is thus more likely to be caused by post-asymptotic giant branch (AGB) stars (Sarzi et al. 2010; Yan & Blanton 2012) or shocks (Rich et al. 2015) than low-luminosity AGN activity. However, if the “ring”-like structure is a real feature, it could be an echo of previous nuclear activity. Given the light travel time from the nucleus to the edge of this feature, the echo would trace nuclear activity on a timescale of $\tau \sim 3000$ yr ago. Further data would be required to determine if this ring-like structure is real, due to the low S/N of these weak emission lines, especially for H/3 and in the center of the galaxy.

While this galaxy does not show evidence for ongoing luminous AGN activity, the timescale for AGNs to vary is much smaller than the characteristic timescale of this outflow. AGNs are observed to change dramatically, turning on and off on timescales of $\sim 10^6 - 10^7$ yr (Keel et al. 2012; Sartori et al. 2018; Shen 2021). The molecular gas outflow we observe would have been launched 4.5 Myr ago, when the galaxy could have had now-faded AGN activity.
3.4. Evolution During the Post-starburst Phase

The evolution of the molecular gas state during the post-starburst phase can provide more information than comparing the average properties to other classes of galaxies. We found in French et al. (2018a) that the CO-traced molecular gas fraction declined during the post-starburst phase, after 90% of the starburst is complete, with a timescale of \( \sim 200 \) Myr. A similar decline has been seen in the CO-traced molecular gas in higher redshift post-starburst galaxies (Bezanson et al. 2022; Suess et al. 2022). The low SFRs during this period of decline cannot be responsible for depleting this gas via consumption or stellar feedback, suggesting that another mechanism like AGN feedback is operating late into the post-starburst phase. The dust fraction is also observed to decline during the post-starburst phase (Smercina et al. 2018; Li et al. 2019), with a timescale consistent with that of the CO-traced molecular gas (Li et al. 2019). Li et al. (2019) considered the evolution of the SFE (traced by SFR/(\( \alpha_{CO} L'_{CO} \))), finding a rapid decline in SFE during the first 200 Myr of the post-starburst phase, which levels off to a shallower decline after 200 Myr post-burst. This two-phase evolution in SFE implies a two-phase evolution in SFR and a faster initial timescale of SFR evolution compared to the CO-traced molecular gas.

Such a two-phase evolution in SFR with post-burst age was observed by Rowlands et al. (2015) in both H\( \alpha \)- and far-IR-based SFRs. A short \( \sim 30 \) Myr decline was followed by a plateau of \( \sim 400 \) Myr. The overall timescale for the SFR to drop was \( \sim 200 \)–\( 300 \) Myr.

We illustrate the evolution of the specific SFR (sSFR) and various tracers of the molecular gas in Figure 11. We plot the sSFR traced by H\( \alpha \) for the three post-starburst samples from French et al. (2015), Rowlands et al. (2015), and Alatalo et al. (2016). Post-burst ages are from French et al. (2018a) and measure the time elapsed since the end of the recent starburst (the age since 90% of the stars were formed). The sSFR trend qualitatively appears to follow that expected from Rowlands et al. (2015) and Li et al. (2019), with a rapid initial decline that

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**Figure 9.** ALMA CO (3–2) observations of S02 with complementary MaNGA (Bundy et al. 2015) observations (MaNGA plateID 8080-3072) accessed via Marvin (Cherinka et al. 2019). Top left: CO (3–2) moment 0 map, with beam size shown in bottom left. The galaxy has a faint trail of gas extending to the lower left. Top right: CO (3–2) moment 1 map, with stellar velocity contours from MaNGA overlaid in the same color scale. The stellar velocity is aligned with the bulk of the molecular gas velocity. The faint component to the lower left is blueshifted with respect to the surrounding stellar velocity field, indicative of an outflowing component. Bottom left: CO (3–2) moment 1 map, with optical emission-line velocity contours from MaNGA overlaid in the same color scale. The ionized gas is disturbed with respect to the stellar velocity. The blueshifted CO component is aligned with the blueshifted ionized gas region, indicating a multiphase outflow. Bottom right: comparison of CO (3–2) moment 0 map with Hubble Space Telescope (HST) F625W image. The blueshifted component to the lower left is aligned with a dust lane in the HST image.
levels off at later times. Rowlands et al. (2015) observed a third phase of more rapid decline after 400 Myr in the Hα SFRs, which we do not observe here. We see no evidence of a significant correlation between age and sSFR for ages >400 Myr using a Spearman’s or Pearson correlation test. This may be driven by differing treatments of the SFR in galaxies in the AGN portion of the BPT diagram in the limiting cases of very low SFRs.

We explore the evolution during the post-starburst phase quantitatively by fitting the sSFR and CO-traced molecular gas fraction trends with two-component linear fits to $x - \ln(y)$, with the two lines required to meet in the middle. This model

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**Figure 10.** Resolved Baldwin–Phillips–Telervich (BPT; Baldwin et al. 1981) diagrams (top row) for S02, shown with diagnostic lines from Kewley et al. (2001) and Kauffmann et al. (2003). Each spaxel is classified using its emission-line ratios. The bottom plot shows the spatial distribution of the spaxels colored by classification. Most of the galaxy has low emission-line fluxes such that the classification is ambiguous but the spaxels that can be classified are in the LINER part of the BPT diagram (with one Seyfert spaxel). This LINER-like signature extends outside of the nucleus over $\sim$5″ (10 spaxels), significantly more than the 2″ FWHM of MaNGA’s spatial resolution (Law et al. 2016). It is thus more likely to be caused by post-AGB stars (Yan & Blanton 2012) or shocks (Rich et al. 2015) than current AGN activity. This galaxy does not have current AGN activity. However, the flickering timescale for AGNs is shorter than the characteristic timescale of the outflow, so the outflow could have been launched by a previous episode of AGN activity.
has four free parameters: the early slope, the late slope, the break point, and a y-offset. We assume a constant uncertainty in sSFR of 0.1 dex and take into account the measured molecular gas fraction uncertainties and upper limits. For this analysis, we do not include the uncertainty on age. For the sSFR-age comparison, the best-fit early slope is 65 Myr, the best-fit late slope is 480 Myr, and the pivot point is 77 Myr. The two-slope fit is significantly preferred over a single-slope fit using either the reduced $\chi^2$ ($\chi^2/\nu_{\text{1 slope}} = 208$ versus $\chi^2/\nu_{\text{2 slope}} = 19$) or Bayesian information criterion (BIC; BIC$_{1 \text{ slope}}$ = $1.5 \times 10^4$ versus BIC$_{2 \text{ slope}}$ = 1326) tests. The best-fit early slope is comparable to the typical duration of the recent bursts (French et al. 2018a) and may be a continuation of the decline in SFR as the burst ended. Given the uncertainties on the derived parameters, the early and late slopes are significantly different. In contrast, fitting the same two-component function to the CO-traced gas fraction–age comparison, there is no significant difference between the early and late slopes. We see no evidence to support a two-phase evolution in the decline of the CO-traced gas with time. These lines are overplotted on Figure 11.

The dense molecular gas to total molecular gas fraction, traced by the $L'_{\text{HCO+}}/L'_{\text{CO}}$ ratio, is proportional to the fraction of the molecular gas reservoir in the denser states probed by HCO$^+$. In several cases, the post-starburst galaxies show evidence that the $L'_{\text{HCN}}$ luminosity is enhanced relative to the $L'_{\text{HCO+}}$, similar to many AGNs and ultraluminous infrared galaxies (ULIRGs; see further discussion in Section 3.6), so we consider $L'_{\text{HCO+}}$ here as a more accurate tracer of the dense gas mass. Most (five out of six) of the post-starburst galaxies have low ($L'_{\text{HCO+}}/L'_{\text{CO}} < 0.04$) fractions, except for R02, which is the youngest post-starburst galaxy in our ALMA-targeted sample. This may indicate a rapid (<100 Myr) decline in the dense gas fraction at the start of the starburst, but a larger sample will be required to determine whether this trend is significant, as it is driven by the observations for a single
galaxy. If we instead consider the dense gas to stellar mass fraction, using an \( \alpha_{\text{HCO}} = 10 \, M_\odot \, (\text{K km s}^{-1} \text{pc}^{-2})^{-1} \), this rapid decline is not observed. These differing trends may be caused by scatter in the CO-traced gas fraction among the sample. Observations of a larger sample will be required to determine whether the dense molecular gas has a rapid early decline similar to that seen in the sSFR or a slower decline throughout the post-starburst phase more like the evolution seen in the CO-traced gas.

### 3.5. Star Formation in the Dense Gas

Previous work on the dense gas in post-starburst galaxies were motivated by the high CO luminosities relative to the low SFRs. In Figure 12, we plot \( L'_\text{CO} \) versus SFR for post-starburst galaxies and comparison samples of other galaxy types. The comparison star-forming and starbursting galaxies from Gao & Solomon (2004b), subregions of nearby star-forming galaxies from Usero et al. (2015), and early-type galaxies from Crocker et al. (2012) show SFRs highly correlated with \( L'_\text{CO} \) luminosities, despite the varying ranges of stellar masses and redshifts. We consider the H\( \alpha \)-traced SFRs for the post-starburst sample here; the impact of SFR tracer on our results is explored further in Section 4.1 and in Appendix B. The post-starburst galaxies are systematically offset to higher \( L'_\text{CO} \) relative to other quiescent galaxies (French et al. 2015). The two highest SFR post-starbursts shown are R02 and R05, from the Rowlands et al. (2015) sample, which uses a different selection method (see Section 2.1). These are also the youngest post-starburst galaxies considered here and have \( L'_\text{CO} \) values consistent with the SFRs. The location of these young post-starbursts on the \( L'_\text{CO}-\text{SFR} \) relation is consistent with the evolution of the SFE (\( \propto \text{SFR} / L'_\text{CO} \)) seen by Li et al. (2019).

Our previous study of the dense gas in two post-starburst galaxies (H02, S05; French et al. 2018b) found low limits on \( L'_\text{HCO} \) and \( L'_\text{HCO+} \), consistent with their low SFRs. Here, we primarily consider the \( L'_\text{HCO+} \) instead of \( L'_\text{HCO} \) to trace the dense gas, as the HCN is likely overestimating the dense gas mass (see further discussion in Section 3.6), although both are shown in Figures 12 and 13. For the four new post-starburst galaxies targeted in this study, we find that the two young post-starburst galaxies from the Rowlands et al. (2015) parent sample (R02 and R05) also have dense gas luminosities consistent with their SFRs (Figure 12). For the two older post-starburst galaxies from the French et al. (2015) parent sample, S02 is not detected in either HCN+ or HCN, at levels either consistent with its low SFR or slightly above. H03 remains offset from the \( L'_\text{HCO+}-\text{SFR} \) relation, but the SFR of this galaxy is highly uncertain (see discussion in Section 4.1).

We consider the ratio of dense molecular gas to total molecular gas traced by \( L'_\text{HCO+} / L'_\text{CO} \) in Figure 13. Five out of six of the post-starburst galaxies have low values of \( L'_\text{HCO+} / L'_\text{CO} \) lower than at least 63% of the comparison galaxies, except for the youngest post-starburst galaxy in the sample, R02. As discussed in Section 3.4, this may be an evolutionary effect with post-burst age. In French et al. (2018b), we observed low HCN/CO ratios from two of the HCN limits plotted here. With the addition of the four new galaxies, as well as the addition of the comparison sample of star-forming galaxy components from Usero et al. (2015), we see that five out of six of the post-starbursts have low HCN/CO ratios.

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15 The conversion factor \( \alpha_{\text{d}} = M_{\text{d}} / L_{\text{d}} \) will scale as \( \alpha_{\text{d}} \propto 2.1 \, n \), where \( n \) is the density of H\(_2\) molecules and \( T_b \) the brightness temperature (Papadopoulos 2007). Gao & Solomon (2004a) use this argument to estimate the conversion factor for HCN given the expected conditions, resulting in a value of \( \alpha_{\text{HCN}} = 10 \, M_\odot \, (\text{K km s}^{-1} \text{pc}^{-2})^{-1} \). The dense gas luminosity to mass conversion factor should be similar for both HCO\(^+\) and HCN (1–0), as they trace similar gas conditions, so we use this same conversion factor for HCO\(^-\). The result shown in Figure 11 will only be affected by differences in \( \alpha_{\text{d}} \), if there is significant variation from source to source.
ratios relative to the comparison samples, though there are some star-forming galaxy components with lower HCN/CO ratios. Five out of six of the post-starburst galaxies have HCN/CO ratios lower than at least 70% of the comparison samples, with the exception of H03. The post-starburst galaxy with high HCN/CO (H03) may have HCN luminosity increased via mechanical heating or cosmic-ray heating, as it has a very high HCN/HCO+ ratio (see discussion in Section 3.6), and the HCN/CO ratio may overestimate the dense molecular gas fraction.

### 3.6. Dense Gas State

Ratios between the dense gas tracers HCN, HCO+, and HNC (1–0) are sensitive to various mechanisms that affect the reliability of these lines as tracers of the dense gas mass. AGNs and some ULIRGs have high HCN/HCO+ ratios (Kohno et al. 2001; Imanishi et al. 2004, 2007; Privon et al. 2015), which have been attributed to IR pumping, X-ray dominated region (XDR)-dominated chemistry, mechanical heating, or cosmic-ray heating (Aalto et al. 2007; Loenen et al. 2008; Bayet et al. 2011; Meijerink et al. 2011; Privon et al. 2015, 2020).

We compare the HCN/HCO+ ratios of the three post-starburst galaxies with both line measurements with other types of galaxies in Figure 14. The HCN/HCO+ ratios of the post-starburst galaxies vary considerably, with scatter across the entire sample of comparison galaxies. This scatter is much larger than the uncertainty on the line ratio measurements. One of the post-starbursts (H03) has a very high HCN/HCO+ ratio (low HCO+/HCN), even compared to AGNs and ULIRGs.

The HNC/HCN ratio is sensitive to the ionization state of the Interstellar Medium (ISM), and can distinguish XDRs from PDRs. We plot the comparison of the HCN, HCO+, and HNC (1–0) ratios in Figure 15. The post-starbursts have similar HNC/HCN values as most of the comparison starbursts and star-forming galaxies, and are consistent with PDR-dominated ionization.

### 4. Discussion

#### 4.1. Star Formation Rates

The measurement of current SFRs in post-starburst galaxies is complicated by a number of factors (see discussion in French 2021, their Section 5). For this work, our goal is to measure the current SFRs (over timescales <10 Myr), with low contamination from other sources of excitation and with accurate correction applied for dust extinction. Contamination from the young stellar populations, AGNs, and shocks would cause the SFRs to be underestimated, while high dust obscuration beyond that probed by Balmer decrement corrections would cause the SFRs to be overestimated. We consider here the comparison of the Hα-based SFRs used above (described in Section 2.3) to other SFR tracers to assess the possible biases in these measurements.

The combination of the [Ne II] 12.8 μm and [Ne III] 15.6 μm lines traces H II regions with relatively low bias compared to other SFR tracers (Ho & Keto 2007; Whitcomb et al. 2020). Dust extinction scales as $A_V/\lambda^2$ in the near- and mid-IR; using the extinction law measured by Wang & Chen (2019), the extinction at the wavelengths of [Ne II] and [Ne III] is 500–800× lower than $A_V$. Thus, the neon-based SFRs will not be subject to underestimation due to dust obscuration, even in...
galaxies with ULIRG-like central dust obscuration. Smercina et al. (2018) measured Ne-based SFRs for a sample of 15 post-starburst galaxies, two of which (S02 and S05) are studied in this work. We compare the Ne-based SFRs to Hα-based SFRs in Figure 16. For the sample of seven post-starburst galaxies with neon detections, we observe no systematic bias between the Hα- and Ne-based SFRs. Of the two galaxies considered here, the measurements of S02 agree well, and the Ne-based SFR for S05 is lower than the Hα SFR. This indicates that neither galaxy has significant obscured star formation. In Appendix B, we consider the impact of using Ne-based SFRs on the Kennicutt–Schmidt relation, finding the post-starburst galaxies to lie offset from the relation formed by star-forming and starburst galaxies, consistent with the results from using Hα-based SFR tracers.

The TIR luminosity is also sensitive to obscured star formation, yet the TIR traces star formation on longer timescales, which can be comparable to the time since the recent starburst. Smercina et al. (2018) found that TIR-based SFRs overestimate the SFR traced by neon for post-starburst galaxies. For the seven post-starburst galaxies with Ne detections and eight galaxies with upper limits, the ratio of SFR-TIR to SFR-Ne is >2. Luo et al. (2022) observed a TIR-based SFR 20× higher than the Ne-based SFR for the post-starburst galaxy IC 860. In Figure 17, we compare the SFRs from TIR and neon for post-starburst galaxies, stacks of starbursting galaxies with varying AGN properties from Stone et al. (2023), and the best-fit relation from star-forming galaxies from Ho & Keto (2007). Each of the Ne-detected post-starburst galaxies and all but one of the upper limits are consistent with SFR-TIR > SFR-Ne. In contrast, the starburst galaxy stacks from Stone et al. (2022) scatter evenly around the Ho & Keto (2007) relation calibrated on star-forming galaxies. We use linmix (Kelly 2007) to further quantify the offset observed for the post-starburst sample (including IC 860) by fitting a linear relation to log(SFR-TIR) versus log(SFR-Ne). If we consider only the post-starburst galaxies with neon detections, the best-fit line indicates a factor 2× offset below the 1:1 line, consistent with our estimate from the median values. If we include information from the 3σ upper limits for neon nondetections, the best-fit line indicates a factor 8× offset for the range of SFR-TIR values. This comparison suggests the TIR overestimates the SFR that would be measured with the Ne lines by 2–8× in post-starburst galaxies. Because this effect is not present in the starbursting sample, it may be due to the longer duration of TIR as a SFR tracer being contaminated by the recent starburst for the post-starburst galaxies. For the analysis of SFR-TIR of the post-starburst galaxies, we thus adopt a correction factor to decrease the SFR-TIR by a factor of 2.

We compare the Hα-based SFRs to TIR-based SFRs from Smercina et al. (2018) for the galaxies from French et al. (2015), H02, H03, S02, and S05, and full SED-fit SFRs (including Herschel photometry) from Rowlands et al. (2015), for R02 and R05, in Figure 16. The TIR-based SFRs are divided by a factor of 2 as described above, to account for the likely overestimate due to the longer duration of this tracer. With this correction, there is no systematic bias between the two SFR indicators, although the scatter is large. We note that for H02 and H03, the large offset indicates there may be obscured star formation. Recently, Baron et al. (2022) found that some samples of post-starburst galaxies have high SFRs ~10–100 M⊙ yr−1 when traced by their IR luminosity. The samples most heavily affected are post-starburst samples chosen to optimize for young post-starburst ages or to not select against AGN activity. We note that the SFRs for the

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16 Excluding IC 860, we observe a 2× offset for the neon detections and a 7× offset for the censored fit including nondetections.
post-starburst galaxies considered here have significantly lower SFRs, even using the highest estimates from the TIR luminosity. We compare the H\(\alpha\)-based SFRs to 1.4 GHz-based SFRs using data from the Very Large Array FIRST survey (Becker et al. 1995). We convert the 1.4 GHz fluxes and flux limits to SFRs following Nielsen et al. (2012) by using the calibrations from Condon (1992) and Yun et al. (2001). Of the galaxies considered here, R02, R05, and H03 are detected by FIRST, and the rest of the galaxies are not detected. The 1.4 GHz flux is likely to be contaminated by any AGN or LINER activity in the post-starburst sample (e.g., Moric et al. 2010), especially for H03, given the large offset between the 1.4 GHz and Br\(\gamma\) indicators.

Another IR line used to calculate SFRs with minimal effects from dust attenuation is the Br\(\gamma\) line (see Pasha et al. 2020). We have conducted a survey of near-IR spectroscopy of the parent samples considered here from French et al. (2015), Rowlands et al. (2015), and Smércina et al. (2018) using Magellan/FIRE (A. Tripathi, K. D. French et al., in preparation). Using the calibration from Kennicutt (1998), we compare the Br\(\gamma\) SFRs to the H\(\alpha\) SFRs in Figure 16. Br\(\gamma\) is detected for R02 and R05. Our data provide useful upper limits on the SFRs for H03 and S02.\(^{17}\) Despite the high SFR \(\sim 5 \ M_\odot\) yr\(^{-1}\) for H03 that would be inferred from its TIR or 1.4 GHz luminosities, H03 is not

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\(^{17}\) Unfortunately, the faint K-band magnitude of H02 prohibited its inclusion in the FIRE sample.
detected in Brγ at a level consistent with its Hα flux. This unusual TIR/Brγ ratio is not seen for other galaxies, even those with extremely high extinction like Arp 220 (Pasha et al. 2020). Further observations, especially NIR and mid-IR (MIR) spectroscopy, will be required of these sources to determine the origin of the dust heating. While in French et al. (2018b) we assigned an upper limit on the SFR for H02, here we use the Hα-based SFRs throughout, motivated by the consistency with the Brγ observations.

The Ne-based SFRs are the best available SFR tracer for this sample, as the Ne lines can trace obscured star formation even at the levels of ULIRGs, the contamination from other excitation sources is low, and the timescale for this SFR tracer is much shorter than the typical post-starburst ages (Ho & Keto 2007; Smercina et al. 2018). Unfortunately, mid-IR spectroscopy is required for this measurement, and not available for the entire sample considered here. We use the cases where both Ne and Hα SFRs are available to test the Hα SFRs for bias (Figure 16) and find the two tracers to be consistent. This consistency indicates that the post-starburst galaxy samples considered here do not typically have obscured star formation missed by the Hα tracer corrected using the Balmer decrement. Two galaxies (H02 and H03) have strong mismatches between the TIR SFR and Hα SFR, yet do not

Figure 16. Comparison of SFR tracers (discussed in Section 4.1) with the Hα-based SFRs used elsewhere in this study. Post-starburst galaxies from French et al. (2015, Rowlands et al. 2015, and Smercina et al. 2018) are shown in black, and the ALMA targets are highlighted in green. All limits are 3σ upper limits. The Hα SFRs are consistent with short-duration IR tracers from neon and Brγ, indicating that the use of Hα is not biased low due to dust obscuration. Smercina et al. (2018) observed a systematic offset between TIR and neon SFRs, such that the TIR-based SFRs were on average 2× higher than the Ne SFRs, likely due to dust heating by young stars. We apply this correction to the TIR SFRs used here. The 1.4 GHz flux is likely to be contaminated by any AGN or LINER activity in the post-starburst sample (e.g., Morić et al. 2010), especially for H03, given the large offset between the 1.4 GHz and Brγ indicators.
For one of these galaxies, we have MIR spectroscopy for which a Ne SFR can be measured. For comparison, we also plot the best-fit line (blue) and scatter (blue dashed) for star-forming galaxies from Ho & Keto (2007) and the stacks of starburst galaxies with varying AGN properties from Stone et al. (2022, upper right). The post-starburst galaxies (with the two targets observed with ALMA in this work, highlighted in green) are systematically below the Ho & Keto (2007) calibration, indicating the TIR-based SFRs are likely overestimating the true SFR. This offset is not seen for starbursting galaxies considered by Stone et al. (2022). Using linmix (Kelly 2007), we fit a linear relation between log(SFR-TIR) and log(SFR-Ne). If we consider only the post-starbursts with neon detections (orange), the best-fit line indicates a factor 2× offset below the 1:1 line; including information from the 3σ upper limits (light blue) indicates a factor 8× offset. This comparison suggests the TIR overestimates the SFR that would be measured with the Ne lines by 2−8× in post-starburst galaxies. Because this effect is not present in the starbursting sample, it may be due to the longer duration of TIR as a SFR tracer, resulting in the TIR-based SFR being contaminated by the recent starburst for the post-starburst galaxies.

Figure 17. Comparison of TIR-based SFRs and neon-based SFRs for post-starburst galaxies observed with Spitzer by Smercina et al. (2018) and Luo et al. (2022) (IC 860). For comparison, we also plot the best-fit line (blue) and scatter (blue dashed) for star-forming galaxies from Ho & Keto (2007) and the stacks of starburst galaxies with varying AGN properties from Stone et al. (2022, upper right). The post-starburst galaxies (with the two targets observed with ALMA in this work, highlighted in green) are systematically below the Ho & Keto (2007) calibration, indicating the TIR-based SFRs are likely overestimating the true SFR. This offset is not seen for starbursting galaxies considered by Stone et al. (2022). Using linmix (Kelly 2007), we fit a linear relation between log(SFR-TIR) and log(SFR-Ne). If we consider only the post-starbursts with neon detections (orange), the best-fit line indicates a factor 2× offset below the 1:1 line; including information from the 3σ upper limits (light blue) indicates a factor 8× offset. This comparison suggests the TIR overestimates the SFR that would be measured with the Ne lines by 2−8× in post-starburst galaxies. Because this effect is not present in the starbursting sample, it may be due to the longer duration of TIR as a SFR tracer, resulting in the TIR-based SFR being contaminated by the recent starburst for the post-starburst galaxies.

have MIR spectroscopy for which a Ne SFR can be measured. For one of these galaxies (H03), we have a strong limit on the Brγ SFR which is consistent with H0. While Brγ is less sensitive to dust obscuration than H0, ULIRG-like central dust densities could still obscure a nuclear star-forming region. Such a mismatch between a quiescent host galaxy and a nuclear starburst would be unusual, as LIRGs and ULIRGs have star-forming regions visible outside of the central regions with high dust obscuration, but we cannot fully rule out the possibility of an obscured region with SFR ∼ 5 M⊙ yr⁻¹ in H02 and H03.

In order to assess the impact of SFR tracer on our conclusions, we reproduce the key figures in this work using the TIR-based SFRs in Appendix B. The SFRs for four galaxies (S02, S05, R02, R05) are comparable, while the SFRs for two galaxies (H02 and H03) are higher. Considering the TIR SFRs instead of the H0 SFRs, our qualitative conclusions do not change. We find that the post-starburst galaxies still lie offset from the Kennicutt–Schmidt relation, and have high L'CO yet consistent L'HCO+ and L'HCN values for their SFRs.

4.2. Interpretation

As galaxies evolve through the post-starburst phase, the galaxies with remaining molecular gas remaining experience an unusual transition in their gas properties. The gas is confined to the central ~kpc, more limited in extent than the optical light or even the young stellar populations. Yet the gas state is such that the typical density is low, as traced by both the lack of strong dense gas emission and by the low CO excitation. What then is suppressing this gas from collapsing to denser states?

The low CO excitation indicates that the bulk of the molecular gas is not being heated. The outflow observed in S02, as well as the outflow observed in CO (2−1) by Smercina et al. (2022) for another post-starburst, provide a clue that relatively low velocity outflows, lower than or close to the escape velocity, may prevent the gas from recollapsing. The origin of these outflows is still unclear. We observe no strong AGN activity in these galaxies, yet because the timescale for AGNs to vary is shorter than the timescale for us to observe these outflows, past AGN activity may have launched these outflows. Alternatively, weak, low-level AGN activity (if the LINER is a low-luminosity AGN) may be enough to sustain quiescence during this phase and deplete the gas over 1−2 Gyr. If weak AGN activity is currently affecting these galaxies, it must be at such a low level as to not result in high CO excitation and not drive AGN-like emission-line ratio maps. We speculate that if the energy coupling of TDEs to the molecular gas is efficient compared to AGN energy coupling, the high TDE rate during this phase may act to provide the
energy source needed to keep this gas from collapsing to denser states and forming stars (see further discussion in Smercina et al. 2022).

A key test for models of feedback in simulations aiming to recreate the galaxy population, including galaxies with rapidly ending star formation, will be to predict the detailed evolution of the densest gas on scales of $n \sim 10^4$ cm$^{-3}$ and at cold temperatures $T < 100$ K.

5. Conclusions

Observations of large fractions of molecular gas remaining in galaxies with recently ended starbursts have raised questions of what mechanisms act to drive galaxies to quiescence. In this study, we present new observations of CO (3–2) observations for three post-starburst galaxies and dense gas tracers for four post-starburst galaxies, combining with literature measurements for a total dense gas sample size of six.

1. The post-starbursts have low excitation as traced by the CO SLED up to CO (3–2), more similar to early-type than starburst galaxies. The low excitation indicates that lower density rather than high temperatures may suppress star formation during the post-starburst phase, as higher temperatures would result in excitation states more like starbursts. Radiative transfer modeling with RADEX supports this picture: the RADEX models favor low densities ($\log n/cm^{-3} \sim 3.4$–3.8) and temperatures ($T \sim 15$–30 K), similar to early-type galaxies and lower than typical starbursts. The low CO excitation is in contrast with the high ISRF intensity (and thus high dust temperatures) in these galaxies, suggesting the molecular gas temperature is decoupled from the dust.

2. The post-starburst galaxies have small CO (3–2) sizes (~250–400 pc) compared to their optical sizes. The CO (3–2) sizes are on average ~6.3× smaller than the $r$-band optical sizes from SDSS images. This result is consistent with the findings of Smercina et al. (2022).

3. Post-starburst galaxies have high molecular gas surface densities for their SFR surface densities, resulting in an offset from the Kennicutt–Schmidt relation, consistent with the findings of Smercina et al. (2022). We find this same result using both optical (H$\alpha$) and IR-SFR tracers (TIR luminosity and [Ne II] 12.8 $\mu m$ + [Ne III] 15.6 $\mu m$), indicating that this offset is not driven by the presence of dusty obscured star formation.

4. One galaxy (S02) displays a blueshifted molecular gas outflow traced by CO (3–2). This galaxy has complementary HST and MaNGA observations, facilitating multiwavelength comparisons. The MaNGA observations show the ionized gas velocity is disturbed relative to the stellar velocity field, with a blueshifted component aligned with the molecular gas outflow, indicative of a possible multiphase outflow. The inferred mass-loss rate is consistent with the CO depletion observed statistically in French et al. (2018a). The energy required to drive this outflow is consistent with lower luminosity AGN/LINERs or TDEs. The feasibility of energy from intermittent AGN activity or from TDEs will depend heavily on the coupling to the molecular gas in these galaxies.

5. Low ratios of HCO$^+$/CO, indicating low fractions of dense molecular gas relative to the total molecular gas, are seen throughout the post-starburst phase beginning ~10–200 Myr after burst ends for five out of six post-starburst galaxies. Most post-starbursts have low HCO$^+/CO$ ratios; the exception is the youngest post-starburst in our sample, suggesting early evolution. Rapid evolution in the dense gas would be consistent with the rapid evolution in sSFR during the early post-starburst phase. However, observations of a larger sample will be required to determine whether the dense molecular gas has a rapid early decline similar to that seen in the sSFR, or a slower decline throughout the post-starburst phase, more like the evolution seen in the CO-traced gas.

6. Post-starburst galaxies have low $L_{\text{HCO}^+}$-traced dense gas luminosities more consistent with their low SFRs than the CO luminosities would indicate, with the exception of the post-starburst galaxy H03 which has a highly uncertain SFR. This is consistent with our previous work (French et al. 2018b) and indicates that the low SFRs in the post-starburst phase are due to a lack of dense gas, in contrast to the large masses of total molecular gas traced by CO (1–0) (French et al. 2015; Rowlands et al. 2015; Alatalo et al. 2016). Our qualitative conclusions do not depend on the SFR tracer used.

7. The three post-starbursts with measured HCN/HCO$^+$ ratios show a large variation, spanning the entire range shown by AGN, ULIRGs, and star-forming galaxies. This may be due to a range of either mechanical heating or cosmic-ray heating of the HCN, but the origin is uncertain.

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Software: Astropy (Astropy Collaboration et al. 2013, 2018), CASA (McMullin et al. 2007), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020).

Appendix A
Spectra and Moment Maps

Moment maps for both the CO (3–2) and HCN (1–0), HCO+ (1–0), and HNC (1–0) data sets are shown in Figures 18 and 19. Extracted spectra are shown in Figures 20 and 21. More information can be found in Section 2.2.

Figure 18. CO (3–2) moment maps (left column: moment 0; middle column: moment 1; right column: moment 2). Data with a signal-to-noise ratio of <3 are masked. The molecular gas has limited spatial extent, with CO sizes <1″, significantly smaller than the optical extents of the galaxies (r-band R50 values 3″72, 1″71, and 3″17 for S02, H02, and H03, respectively). S02 has a blueshifted component to the lower left, which we explore further in Figures 7–9.
Figure 19. Moment 0 (left), moment 1 (middle), and velocity dispersion (right) maps for the HCO\(^+\) (1–0) emission for the three galaxies with detected emission.

Figure 20. Extracted CO (3–2) spectra for each galaxy. For easier visualization, spectra are binned to 5 km s\(^{-1}\) (dark blue lines). A horizontal center line (gray) and uncertainty bands per 5 km s\(^{-1}\) channel (dotted gray) are added for comparison. Vertical gray lines represent the integration range for determining the total flux.
Appendix B

Infrared Star Formation Rates

In Figures 22, 23, and 24, we consider the impact of using the TIR luminosity instead of Hα to trace the SFR in the post-starburst sample. A full comparison of the SFR tracers for this sample can be found in Section 4.1. Our qualitative conclusions do not change, given this sample. We observe the post-starburst galaxies to lie offset in the CO-traced gas versus SFR plot, while they lie consistent with the comparison samples in the HCO⁺ versus SFR plot. Even when using the TIR luminosity as a SFR tracer, the offset observed in the left panel of Figure 23 is significant. Even if all of the CO upper limits placed the CO nondetected post-starbursts above the relation, with high SFEs, the chances of finding as many post-starbursts with low SFE < 10⁹ yr⁻¹ is low. Using the star-forming, starbursting, and early-type galaxies to define the range of expected SFE and scatter, we use a Monte Carlo analysis to determine that we would find the large fraction of low SFE post-starbursts only 1.7% of the time.

Figure 21. Extracted spectra of the three dense gas tracers (HCN (1–0), HCO⁺ (1–0), and HNC (1–0)) for each galaxy. For easier visualization, spectra are binned to 30 km s⁻¹ (dark blue lines). A horizontal center line (gray) and uncertainty bands per 30 km s⁻¹ channel (dotted gray) are added for comparison. Vertical gray lines represent the integration range for determining the total flux.
Figure 22. Same as Figure 6, but with IR-SFR indicators used instead for the post-starburst galaxy sample (left: TIR; right: [Ne II]). Molecular gas surface density vs. SFR surface density for post-starburst galaxies from this work and from Smercina et al. (2022) with CO (2–1) sizes, as well as comparison samples of star-forming galaxies from de los Reyes & Kennicutt (2019) and starbursting galaxies from Kennicutt & De Los Reyes (2021). The best-fit relation from Kennicutt & De Los Reyes (2021) for the total gas density vs. star formation density is plotted in gray, with a dotted line indicating a factor of $10^x$ below the relation. The post-starburst galaxies have very high molecular gas surface densities, yet they lie below the comparison galaxies, with low star formation rate surface densities for their molecular gas surface densities. Our qualitative conclusions here do not depend on the SFR tracer used.

Figure 23. Same as Figure 12, but with IR-SFR indicators used instead for the post-starburst galaxy sample. Left: $L'_{\text{CO}}$ vs. SFR. Early-type galaxies (Crocker et al. 2012), starburst and star-forming galaxies (Gao & Solomon 2004b), and star-forming galaxy components (Usero et al. 2015) are correlated with low scatter, but post-starburst galaxies (French et al. 2015) have low SFRs for their CO luminosities. Black squares indicate post-starburst detections and arrows indicate 3σ upper limits. Filled squares indicate the ALMA targets considered here (including two galaxies from the Rowlands et al. 2015 sample). Middle: $L'_{\text{CO}}$ vs. SFR for the same samples of galaxies. The post-starburst galaxies are more consistent with the comparison samples in their dense gas–star formation relations. The post-starburst galaxies have dense molecular gas properties consistent with either early-type galaxies or lying between the star-forming and early-type samples. Our qualitative conclusions here do not depend on the SFR tracer used.
Figure 24. Same as Figure 13, but with IR-SFR indicators used instead for the post-starburst galaxy sample. Plot colors are the same as 23. Left: dense gas luminosity ratio $L_{\text{HCO}}/L_{\text{CO}}$ for the same samples as Figure 12. Post-starburst galaxies have low ratios of dense molecular gas to total molecular gas compared to other types of galaxies, although this may evolve rapidly with time during the early post-starburst phase (Figure 11). Right: dense gas luminosity ratio $L_{\text{HCO}}/L_{\text{CO}}$ for the same samples. The post-starburst galaxy with high HCN/CO (H03) may have HCN luminosity increased via mechanical heating or cosmic-ray heating, as it has a very high HCN/CO + ratio (see discussion in Section 3.6), and the HCN/CO ratio may overestimate the dense molecular gas fraction. Our qualitative conclusions here do not depend on the SFR tracer used.

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