After The Fall: Resolving the Molecular Gas in Post-starburst Galaxies

Adam Smercina1, John-David T. Smith2, K. Decker French3,4, Eric F. Bell5, Daniel A. Dale6, Anne M. Medling2,7, Kristina Nyland8, George C. Privon9,10, Kate Rowlands11, Fabian Walter12, and Ann I. Zabludoff13

1 Astronomy Department, University of Washington, Seattle, WA 98195, USA; asmerc1@uw.edu
2 Ritter Astrophysical Research Center, University of Toledo, Toledo, OH 43606, USA
3 Department of Astronomy, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA
4 National Center for Supercomputing Applications, 1205 W. Clark Street, Urbana, IL, 61801, USA
5 Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
6 Department of Physics & Astronomy, University of Wyoming, Laramie, WY 82071, USA
7 ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia
8 U.S. Naval Research Laboratory, 4555 Overlook Avenue SW, Washington, DC 20375, USA
9 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903, USA
10 Department of Astronomy, University of Arizona, Steward Observatory, Tucson, AZ 85721, USA
11 AURA for ESA, Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
12 Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany
13 Department of Astronomy, University of Florida, 211 Bryant Space Sciences Center, Gainesville, FL 32611, USA

Received 2021 July 26; revised 2022 March 9; accepted 2022 March 9; published 2022 April 25

Abstract

Post-starburst (PSB), or “E + A,” galaxies represent a rapid transitional phase between major, gas-rich mergers and gas-poor, quiescent, early-type galaxies. Surprisingly, many PSBs have been shown to host a significant interstellar medium (ISM), despite theoretical predictions that the majority of the star-forming gas should be expelled in active galactic nuclei— or starburst-driven outflows. To date, the resolved properties of this surviving ISM have remained unknown. We present high-resolution ALMA continuum and CO(2–1) observations in six gas- and dust-rich PSBs, revealing for the first time the spatial and kinematic structure of their ISM at sub-kpc scales. We find extremely compact molecular reservoirs, with dust and gas surface densities rivaling those found in (ultra)luminous infrared galaxies. We observe spatial and kinematic disturbances in all sources, with some also displaying disk-like kinematics. Estimates of the internal turbulent pressure in the gas exceed those of normal star-forming disks by at least 2 orders of magnitude, and rival the turbulent gas found in local interacting galaxies, such as the Antennae. Though the source of this high turbulent pressure remains uncertain, we suggest that the high incidence of tidal disruption events in PSBs could play a role. The star formation in these PSBs’ turbulent central molecular reservoirs is suppressed, forming stars only 10% as efficiently as starburst galaxies with similar gas surface densities. “The fall” of star formation in these galaxies was not precipitated by complete gas expulsion or redistribution. Rather, this high-resolution view of PSBs’ ISM indicates that star formation in their remaining compact gas reservoirs is suppressed by significant turbulent heating.

Unified Astronomy Thesaurus concepts: Post-starburst galaxies (2176); Dust continuum emission (412); Galaxy evolution (594); Galaxy quenching (2040); Molecular gas (1073)

1. Introduction

Major mergers represent one of the most rapid evolutionary pathways available to galaxies. In the current merger paradigm, colliding gas is heated in shocks, which quickly dissipate and trigger both starburst events and significant gas inflow toward the central potential, forming compact molecular reservoirs (Barnes & Hernquist 1991, 1996; Renaud et al. 2015; Sparre & Springel 2016). Dense, rotating gas disks form rapidly from these nuclear reservoirs—as found, for example, in nearby ultraluminous infrared galaxies (ULIRGs; e.g., Sakamoto et al. 1999; Scoville et al. 2017). In contrast, the majority of isolated elliptical galaxies—the predicted end-state of such major mergers—lack the substantial cool gas and dust reservoirs found in star-forming galaxies (Fall 1979; Barnes 1992; Cappellari et al. 2013; Young et al. 2014; typical molecular gas-to-stellar mass fractions of 0.01%–1%). If starbursting systems are the progenitors of many such “red-and-dead” early-type galaxies (ETGs), the rarity of observed “transitioning” galaxies suggests that their significant interstellar medium (ISM) transformation must have been rapid (~1 Gyr; Barro et al. 2014; Schawinski et al. 2014). The details of this transition from molecular gas-rich to gas-poor remain unclear.

Post-starburst galaxies (PSBs) are a rare galaxy class existing between these two crucial evolutionary phases. Though cataloged using a number of different classification schema, they are generally defined as galaxies that have experienced a significant decline in star formation rate (SFR) from a previous peak. Classical PSBs—“E(K)+As” (Dressler & Gunn 1983; Couch & Sharpeles 1987)—are galaxies with little to no nebular line emission, but a uniquely dominant ~100 Myr old stellar population—only possible if star formation was shut off very rapidly. While some PSBs reside in galaxy clusters, most are found in the field, where they are often identifiable as major merger remnants in Hubble Space Telescope (HST) imaging (Zabludoff et al. 1996; Yang et al. 2006; Chandar et al. 2022). Thus, these PSBs provide a unique window onto the rapid time steps following a major merger.

In the established picture from hydrodynamical simulations, galaxies’ molecular fuel is expelled in the end stages of major
mergers by powerful feedback from star formation and active
galactic nuclei (AGN) prior to and during the PSB phase
(Hopkins et al. 2006, 2008; Snyder et al. 2011). In direct
contrast to this prediction of bulk ISM expulsion, recent work
has found that many PSBs host large reservoirs of molecular
gas (French et al. 2015; Rowlands et al. 2015; Alatalo et al.
2016) and significant dust emission in the near- and far-infrared
(Alatalo et al. 2017; Smercina et al. 2018; Li et al. 2019). These
reservoirs are unlike “typical” galaxies’ ISM, as they exhibit
unusually bright, pure rotational molecular hydrogen (H₂)
emission (Smercina et al. 2018)—indicative of a warm,
turbulent molecular ISM. Though any interpretation has so
far been limited by the relatively coarse physical resolutions of
the underlying observations, star formation in these galaxies
may be turbulently suppressed from forming stars efficiently
(Smercina et al. 2018). Supportive of their possibly inefficient
star formation, these galaxies exhibit an observed deficit of
dense (i.e., “prestellar”) gas, from the Atacama Large
Millimeter/submillimeter Array (ALMA) limits on their HCN and HCO⁺
emission (French et al. 2018b).

While these discoveries have significantly advanced our
understanding of the intermediate stages in the merger-driven
evolutionary pathway, given their local rarity and, thus, the
large typical distance of PSB samples (>100 Mpc), it has not
been possible to investigate the structure and kinematics of the
ISM in gas-rich PSBs. Where does their remaining ISM reside
and is it forming stars as efficiently as expected in more
rapidly star-forming systems? This lack of detail contrasts
significantly with galaxies at the beginning (e.g., Ueda et al.
2014; Scoville et al. 2017) and end (e.g., Ledo et al. 2010) of
the major merger sequence—a gap that must be filled in order
to test and refine our understanding of the physical processes
driving this rapid evolutionary transition.

In this paper, we present, for the first time, high-resolution
ALMA observations of six PSB galaxies, in the CO(2–1)
230.538 GHz line and the adjacent 1.3 mm continuum.

### 2. Observations and Reduction

Our ALMA intermediate baseline observations were taken
across Cycles 3 and 4—for project numbers 2015.1.00665.S
and 2016.1.00980.S, respectively (see Table 1). The Cycle 3
observations were obtained throughout the period from 2015
December to 2016 July, while the Cycle 4 observations were
taken in 2016 July (one source) and 2016 October. Observations
were obtained in relatively compact configurations, with
maximum baselines ranging from ∼300 m–3 km, for angular
resolutions of ∼175 (Cycle 3) and ∼0.2” (Cycle 4).
Additionally, four of the six sources were supplemented
with 7 m compact array (ACA) observations.

All observations were obtained in receiver Band 6, with four
spectral windows; each spectral window was set to a full
bandwidth of 1875 MHz. One of the four windows was centered
on the redshifted CO(2–1) line (rest frequency 230.538 GHz)
for each source, while the remaining three windows were
dedicated to dust continuum emission. The line spectral
windows were set to 3.90 MHz (∼5.4 km s⁻¹) resolution.
During both cycles, the three continuum-dedicated windows for
each source were set to fixed 31.25 MHz (∼40 km s⁻¹)
resolution.

The data were pipeline-calibrated and further reduced using
the Common Astronomy Software Applications package
(CASA; McMullin et al. 2007) version 5.1.0. Where available,
the Cycle 3 12 m, Cycle 4 12 m, and ACA observations were
combined in the UV plane, in order to provide both high
resolution and sensitivity to more diffuse/extended emission.
Self-calibration was performed on one source (0480). Briggs
weighting with Robust = 0.5 was adopted for all sources. We
used the tclean task (based on the CLEAN algorithm;
Högbom 1974) to image the continuum, using the three
dedicated continuum spectral windows. Further iterations of
tclean were run on the continuum-subtracted data in the line-
centered spectral windows, using hand-chosen apertures, until
approximately uniform residual images remained.

### 3. Results

Here, we present the results of our multicycle ALMA campaign
to resolve the ISM properties of six PSBs. In Section 3.1, we first
provide estimates of the cold dust continuum emission at 1.3 mm
in each of the six galaxies, followed by the resolved properties
of their CO(2–1) emission (Section 3.2), including their spatial
(Section 3.2.1) and kinematic (Section 3.2.2) structure. Derived
properties, such as 1.3 mm flux densities, 2D elliptical Gaussian
fits to the CO emission, and integrated CO line luminosities, are
given in Table 2. Also given in Table 2 are ratios of the CO(2–1)
integrated luminosity measured in this work to IRAM single-dish

**Table 1**

| Galaxy | (F15) | R.A. | Decl. | Cyc. 3 (12 m) | Cyc. 3 (7 m) | Cyc. 4 (12 m) | Cont. RMS | Line RMS |
|--------|------|------|------|-------------|-------------|-------------|----------|---------|
| (S18)  | (2)  | (3)  | (4)  | (5) (min)  | (6) (min)  | (7) (min)  | (mJy/beam)| (mJy/beam) |
| 0379_579_51789 | S15 | 22:55:06.80 | +00:58:39.9 | 28 | 87 | ... | 0.033 | 0.94 |
| 0480_580_51989 | H08 | 09:48:18.68 | +02:30:04.2 | 9.0 | ... | 31 | 0.026 | 0.62 |
| 0570_537_52266 | SO5 | 09:44:26.96 | +04:29:56.8 | 36 | 140 | 192 | 0.0091 | 0.44 |
| 0637_584_52174 | S14 | 21:05:08.67 | −05:23:59.4 | 18 | 54 | ... | 0.044 | 1.4 |
| 2360_167_53728 | H02 | 09:26:19.29 | +18:40:41.0 | 4.5 | ... | 9.0 | 0.036 | 1.2 |
| 2777_258_54554 | H03 | 14:48:16.05 | +17:33:05.9 | 7.5 | 28 | ... | 0.071 | 2.0 |

Note. (1)–(2) Galaxy ID in SDSS Plate_Fiber_MJD notation, following Smercina et al. (2018), as well as the E + A ID assigned in French et al. (2015). (3)–(4) Right ascension and declination. The total observation time, across all execution blocks, with the: (5) 12 m array in Cycle 3; (6) 7 m array in Cycle 3; and (7) 12 m array in Cycle 4. (8) RMS of the continuum image. (9) Line RMS in each 5.4 km s⁻¹ channel.

15 Estimated at 220.19 GHz.
Table 2
Properties of the PSB Sample

| Galaxy | $z$ | $D_h$ (Mpc) | $L^\text{IR}_{5000}$ (L$_\odot$) | $L^\text{CO2–1}_{\text{ALMA}}$ (10$^7$ K km s$^{-1}$ pc$^2$) | $L^\text{CO2–1}_{\text{IRAM}}$ (10$^7$ K km s$^{-1}$ pc$^2$) | $M_{\text{H}_2}$ (10$^8$ M$_\odot$) | $f_{\text{obs}}$ (1.3 mm) (mJy) | $f_{\text{obs}}$ (1.3 mm) (SFL) | $\theta_{\text{maj}} \times \theta_{\text{min}}$ ($\arcsec$) | $\theta_{\text{maj}} \times \theta_{\text{min}}$ (SFL) | $f_{\text{core}}$ (%) |
|--------|-----|------------|-------------------------------|-----------------------------------|-------------------------------|-----------------|---------------------|---------------------|-----------------|-----------------|-----------------|
| 0379   | 0.053 | 247.2     | 9.74                          | 0.95                             | 4.45 ± 0.16                   | 5.76 ± 1.24    | 2.7        | <0.25              | 0.91 ± 0.85      | 81                |
| 0480   | 0.060 | 230.9     | 11.18                         | 0.22                             | 39.6 ± 0.95                   | <0.83          | 27.7       | 7.54 ± 0.22       | 0.20 ± 0.17      | 95                |
| 0570   | 0.047 | 215.3     | 9.70                          | 0.23                             | 5.77 ± 0.89                   | <2.67          | 2.0        | <1.66             | 0.29 ± 0.20      | 46                |
| 0637   | 0.083 | 390.2     | 10.24                         | 1.42                             | 20.0 ± 2.1                    | 3.25 ± 0.91    | 9.3        | <0.45             | 0.99 ± 0.78      | 63                |
| 2364   | 0.054 | 250.8     | 10.51                         | 0.30                             | 25.0 ± 4.6                    | 1.41 ± 0.53    | 14.7       | <0.69             | 0.29 ± 0.26      | 80                |
| 2777   | 0.045 | 206.7     | 10.86                         | 0.55                             | 147 ± 51                      | 0.67 ± 0.24    | 69.4       | 1.00 ± 0.35       | 0.75 ± 0.48      | 64                |

Note. (1) Galaxy ID, given as the SDSS plate number, following Smercina et al. (2018). (2)–(3) The optical redshift, $z$, measured from the SDSS spectrum, and the corresponding luminosity distance, $D_h$, adopted throughout this paper, assuming a Planck Collaboration et al. (2016) cosmology. (4) TIR luminosity, from the Smercina et al. (2018) SED fitting. (5) Physical resolution of the elliptical beam, averaged over both axes. (6) Integrated CO(2–1) line luminosity from fits to the velocity profiles. The uncertainties are assessed as the standard deviation of 10^4 bootstrap fits to each profile. (7) Ratio of integrated CO(2–1) line luminosity measured from IRAM (French et al. 2015) and ALMA (this work) observations. The formal uncertainties were incorporated from both measurements; < denotes an upper limit. Some sources' IRAM measurements may be more uncertain than their formal errors; see Section 3.3 for discussion. (8) Total molecular gas mass estimated from $L^\text{CO2–1}_{\text{IRAM}}$, assuming a Galactic CO-to-H$_2$ conversion factor of $\alpha_{\text{CO}} = 4.35$ (K km s$^{-1}$ pc$^2$)$^{-1}$ and a $^{12}$CO(2–1)/CO(1–0) line ratio of $R_{\odot} = 0.59$. (9) Measured 1.3 mm continuum flux density; < denotes an upper limit. (10) Ratio of observed 1.3 mm flux density to the expectation from the best-fit TIR Draine & Li (2007) model SED (Smercina et al. 2018). (11) FHWMs along the major and minor axes of 2D elliptical Gaussian fits to the CO(2–1) moment 0 maps. All sources’ FHWMs correspond to the respective beam widths, i.e., all six galaxies contain unresolved CO “cores.” (12) Fraction of CO(2–1) emission within 3$\sigma$ of the center—i.e., the fraction in the unresolved “core” (expressed as a percentage). Here, $\sigma$ is used relative to the 2D Gaussian fit, as the radius containing 68% of the light.

measurements. We discuss these ALMA/single-dish comparisons at the end of Section 3.2.2.

The six PSBs in this sample were originally identified in the Sloan Digital Sky Survey (SDSS), but have since been assigned unique identifiers through follow-up study. Throughout this paper, we refer to the PSBs by their SDSS plate numbers—e.g., 0379, 0480, 0570, 0637, 2360, and 2777. The full plate–fiber–MJD identifiers published in Smercina et al. (2018) can be found in Table 1, and their corresponding numerical designations, adopted by French et al. (2015), are listed in Table 2.

3.1. Continuum Emission

Measurements of the cold dust continuum at 1.3 mm were performed on the continuum images described in Section 2. For sources with 1.3 mm detections, apertures were chosen by eye. The 1.3 mm apertures coincide with the optical center of the galaxy in all detected cases (see Figure 2). For nondetections, continuum apertures were chosen based on the detected CO emission sizes (see Section 3.2.1), and limits were evaluated within these apertures at the 3$\sigma$ level (where $\sigma$ is the image RMS). The flux densities at 1.3 mm, and corresponding uncertainties, are given in Table 2.

We compare the 1.3 mm continuum to the model fits to the infrared (IR) spectral energy distributions (SEDs; 3–500 $\mu$m) presented in Smercina et al. (2018). These fits use the method of Dale & Helou (2002), applied to the dust models of Draine & Li (2007). The four nondetections, as well as 2777, are in good agreement with the best-fit IR SED models. 0480, however, displays an excess of emission at 1.3 mm—$\sim 3 \times$ greater than expected from the best-fit SED. Far-IR and submillimeter excess emission has been observed in nearby galaxies, such as in low-metallicity dwarf irregulars (e.g., Dale et al. 2012) and in unique galactic environments heavily populated by polarized, rotating dust grains (e.g., Murphy et al. 2010). However, 0480 is unlikely to be of low metallicity, and 1.3 mm is significantly higher energy than the rotating dust grain emission. This submillimeter excess also does not follow the expectation for free–free emission from obscured star formation, as 0480’s radio emission (3 GHz from the VLA Sky Survey (VLASS), Lacy et al. 2020; 1.4 GHz from the Faint Images of the Radio Sky at Twenty-cm (FIRST) survey, Becker et al. 1995) lies $\sim 2.5 \times$ below the radio–IR correlation—a statistically significant deficit, given the claimed scatter in the radio–IR correlation of 0.26 dex, or a factor of $\sim 1.8$ (e.g., Yun et al. 2001; Bell 2003). We show the full IR–radio SED in Appendix A. Whatever the source of this “anomalous” emission, it is not likely to be due to star formation, and it does not significantly affect the estimate of 0480’s total IR (TIR) luminosity.

We show the continuum images for 0480 and 2777 in Figure 1. Both galaxies were observed with sub-kpc physical resolution ($\sim 220$ and $\sim 550$ pc, respectively). In both cases, the 1.3 mm continuum emission emanates from a point source, indicating that the dust reservoirs are highly compact. To estimate their dust column densities, we assume that the 1.3 mm emission is associated with their considerable global dust masses (Smercina et al. 2018; likely, given the consistency with their global IR SEDs). As both 0480’s and 2777’s continuum emission is unresolved, we divide their dust masses (calculated in Smercina et al. 2018) by the size of the resolving beam (see Table 2), yielding dust mass surface densities, $\Sigma_{\text{dust}}$, of 3200 and 527 $M_\odot$ pc$^{-2}$, respectively—comparable to (and even exceeding) the dust surface densities seen in nearby ULIRGs (e.g., Arp 220; Scoville et al. 2017). Following typical prescriptions (Predehl & Schmitt 1995; Güver & Özel 2009), the visual extinction can be estimated from the dust column density as

$$A_V \approx \frac{\Sigma_{\text{dust}}}{2 \times 10^{21} \text{cm}^{-2}}.$$  

Adopting a nearby galaxy–like dust-to-gas ratio of 1% (Sandstrom et al. 2013), this gives $A_V$ of $\sim 2 \times 10^4$ and $\sim 3300$, respectively. Since any distributed dust emission would reduce the inferred column densities, we regard these as illustrative upper limits. Though illustrative, these estimates indicate that the dusty reservoirs in these PSBs are unusually compact.
3.2. CO(2–1) Emission

3.2.1. Morphology

In Figure 2, we show the CO(2–1) Moment 0 integrated intensity, the Moment 1 intensity-weighted velocity, and the Moment 2 intensity-weighted velocity dispersion maps for the six PSBs. Pixels were clipped at 3.5× the channel RMS, following computation of the moments of the spectral cube. The CO emission in all six sources is highly compact. The sizes were determined by fitting 2D elliptical Gaussian functions to each Moment 0 image. All six sources exhibit unresolved “cores”—the FWHMs recovered from the elliptical fits are equivalent to the beam dimensions. The fraction of emission in the unresolved core varies for each source, ranging from 46% in 0570—in which the emission arises from three individual compact clumps—to >95% in 0480.

Figure 3 shows the CO emission of two PSBs (0379 and 0570) on the same spatial scale as HST observations of their starlight. The CO overlaid on the WFC3 F438W/F625W images (GO 11643; PI Zabludoff) highlights the compactness of the molecular gas relative to the galaxies’ optical extents, as well as its disturbed morphology. In one of these sources, 0379, the CO emission is offset from the optical center, and is instead coincident with a faint dust lane.

Though the resolution and global morphology are not uniform across the sample, most of the CO emission in the sample is compact and found on sub-kpc scales. In Figure 4, we compare the approximate CO half-light radii of these six PSBs to that of their stellar emission, and contrast this measure of gas-to-stellar compactness with a sample of nearby star-forming galaxies (from Regan et al. 2006) and ETGs from the ATLAS3D survey (Davis et al. 2013). The molecular gas in our PSB sample is, on average, >10× more compact than that of a comparable sample of “normal” star-forming galaxies, both in absolute scale and relative to their stellar emission. The compactness of the PSBs’ gas is more comparable to the most compact ETGs, though with ∼10× the gas masses.

3.2.2. Kinematics

In Figure 2 (right column), we show the CO(2–1) velocity profiles for the six galaxies. The profiles were extracted from apertures drawn to match the shapes of the emission in the clipped Moment 0 maps shown in Figure 2. Aperture selection and spectral extraction were performed using CASA. The profiles were fit with up to three Gaussian components. Also shown are profiles with the central “core” subtracted—i.e., the “core” region is defined using a circular radius equal to 3× the average width of the 2D elliptical Gaussian fits (shown as orange ellipses in the left column of Figure 2). As the bulk of the gas in five of the six galaxies is spatially unresolved (Section 3.2.1), we do not perform any sophisticated disk modeling; our kinematic analysis is limited here to the identification of multiple components. The results for each of the six galaxies are summarized below.

0379: best fit by a two-component model, with the smaller component centered at the galaxy’s systemic velocity. The larger component corresponds entirely with the CO “core,” and it is both spatially and kinematically off-center with respect to the galaxy’s optical center, by ∼2 kpc and ∼71 km s⁻¹.

0480: a distinctive “double-peak” profile, typically suggestive of rotation. The CO in this system is almost entirely in the “core”—it is unresolved at the achieved ∼200 pc physical resolution. The unresolved nature of the emission precludes us from classifying it as a “rotating disk,” though the gas certainly possesses high–angular momentum content.

0570: best fit with two components, roughly symmetric around the systemic velocity. It is unlikely that this indicates rotation, however, as 0570′s CO field is highly asymmetric, with three spatially distinct “clumps.” The core, and brightest, of these clumps is cospatial with the optical center. The second brightest of the clumps appears to overlap with a dust lane.

0637: best fit with three components—one central, broad component, and two symmetric “wings,” red- and blue-shifted by ∼200 km s⁻¹. These symmetric wings correspond directly to the two spatially symmetric patches of emission to the north.
and south of the central core (see Figure 2), each extending several kpc along the galaxy’s minor axis. These emission wings are oriented perpendicular to 0637’s visible major axis in SDSS. We tentatively characterize these features as consistent with outflowing gas. The gas velocity is quite slow ($\sim 200$ km s$^{-1}$) compared to the fast AGN- and star formation–driven outflows seen at high redshift (e.g., Sell et al. 2014), and may be more comparable to local “slow-boil” winds, such as in the nearby galaxy M82 (e.g., Leroy et al. 2015). This could also be a relic of past nuclear feedback.

2360: a strong central peak is recovered, along with a faint, broader component. The majority of the emission is located...
within the central core, with some faint extended “patchy” emission at larger radii. Both the velocity peak and the broad underlying component appear to originate in the central core, while the kinematics of the extended emission mirror the central peak velocity profile. There does not appear to be strong rotation.

Figure 3. Visual demonstration of the compactness of the PSBs’ CO emission. The CO emission in 0379 (left) and 0570 (right) is overlaid in green on archival HST WFC3 F438W/F625W images. The images are shown in the HST reference frame, with roll angles of 64° and 27° (counterclockwise), respectively. The images were scaled using a square root stretch and are displayed at equivalent physical scale. In both cases, the CO emission is highly compact relative to the optical extent. 0379’s is offset from the optical center, coincident with a faint dust lane. Both galaxies’ gas exhibits a disturbed morphology, but with bright cores hosting the majority of the emission.

Figure 4. Comparison of the stellar and CO sizes of the PSBs and other galaxy samples. The stellar half-light radius (from SDSS imaging; French et al. 2015; Smercina et al. 2018) is plotted against the CO half-light radius for the six PSBs (filled circles; this work), color-coded by their TIR luminosity. The PSBs are compared against a sample of nearby star-forming galaxies (Regan et al. 2006) and ETGs from the ATLAS3D survey (Davis et al. 2013). The CO half-light radii for the ATLAS3D galaxies are all upper limits (these sizes reflect the “maximum extent” of the CO emission). The dashed line shows a one-to-one relation, which the galaxies in the star-forming comparison sample approximately follow. $R_{50,CO}$ is formally an upper limit (marked by the downward arrows) for five of the six PSBs, as their core fractions ($f_{core}$) are >50% and our ability to probe the 50% radius is limited by resolution—i.e., the observed 50% radius is governed by the beam profile, rather than the physical emissive region. On average, the CO in our PSB sample is $>5\times$ more compact than the normal galaxy sample, despite stellar half-light radii similar to the normal galaxy sample. Roughly half of the ATLAS3D ETGs exhibit upper limits on their CO sizes comparable in compactness to the upper limits on the PSBs.
2777: similar kinematics to 2360, with a central peak and a broader underlying component. As with 2360, the majority of the emission is within the central core, with slightly more extended emission at larger radii. Both the velocity peak and the broad underlying component again appear to originate in the central core, while the kinematics of the extended emission mirror the central peak velocity profile. There is no indication of strong rotation.

All six galaxies, with the exception of the completely unresolved 0480, exhibit “patchy” structure in their velocity dispersion maps. The average velocity dispersions are substantially higher at these physical scales than in “typical” nearby galaxies (e.g., Sun et al. 2018, on comparable physical scales), with most of the gas in all six galaxies exhibiting \( \sigma_{\text{disp}} \gg 10 \, \text{km} \, \text{s}^{-1} \), and up to 100 \( \text{km} \, \text{s}^{-1} \) in some cases. 0637 is the only galaxy with distinct emission peaks perpendicular to the galaxy, which we identify as a potential outflow. Both 2360 and 2777 exhibit broad velocity components, associated with more spatially extended emission, which could be suggestive of outflowing gas (for example). Without higher-resolution observations, however, this remains highly speculative.

### 3.3. Molecular Gas Mass and Surface Density

We calculate the integrated CO(2–1) luminosities, following Solomon et al. (1997), as

\[
L'_\text{CO} = 3.25 \times 10^6 (1 + z)^{-3} \nu_{\text{obs}}^{-2} S_{\text{CO}} D_{\odot}^2, \tag{2}
\]

where \( z \) is the redshift, \( \nu_{\text{obs}} \) is the observed frequency of the line in GHz, \( D_{\odot} \) is the luminosity distance in Mpc (from Smercina et al. 2018, assuming the Planck Collaboration et al. 2016 cosmology), and \( S_{\text{CO}} \) is the integrated line flux in Jy km s\(^{-1}\), calculated by integrating the multicomponent velocity profile fits (the red curves in Figure 2).

We compare our integrated CO(2–1) line luminosities to the estimates in French et al. (2015), which presented IRAM single-dish observations of both CO(1–0) and CO(2–1). The ratios of the IRAM measurements to our corresponding ALMA measurements are given in Table 2. Our inclusion of 7 m ACA observations was intended to recover any emission on large scales captured by the single-dish observations that may be resolved out by our high-resolution 12 m observations. For three of the six galaxies, the integrated CO(2–1) fluxes from ALMA and IRAM are relatively consistent—they formally agree within 2\( \sigma \). 0637 is slightly discrepant at 2.5\( \sigma \), and we find that its IRAM spectrum is particularly noisy and is statistically consistent with the best-fit velocity profile to the ALMA data. The remaining two galaxies, 0379 and 0480, are discrepant at >3.5\( \sigma \), with significantly more flux estimated for 0379 with IRAM and significantly less flux for 0480 (0480 is formally a nondetection with IRAM). We rule out the possibility that this discrepancy in 0379 is due to resolving out extended emission in the ALMA observations, as the IRAM beam is 11" and the largest angular scale of our ALMA observations is 19"4, due to the inclusion of the 7 m ACA. This galaxy is one of the most marginal detections of the French et al. (2015) sample, and the disagreement may be due to uncertainties in the flux calibration between the samples, or poor continuum subtraction. A flux calibration or continuum subtraction issue seems to be the only likely explanation for the “missing” flux in the IRAM observations for 0480. In summary, these ALMA observations presented here appear to be broadly consistent with the existing single-dish observations, but there are some subtleties associated with comparing the two samples, due to the order-of-magnitude higher signal-to-noise ratios of these observations. We note that if the fluxes for any of these sources were indeed higher (to match the IRAM measurements), this would only increase the high molecular gas densities we observe for these objects, and would not affect our qualitative conclusions.

We convert the calculated CO(2–1) luminosities, \( L'_\text{CO}(2–1) \), to total mass of molecular gas, \( \text{M}_{\text{Mol}} \), assuming a Galactic CO-to-H\(_2\) conversion factor\(^{16} \) of \( \alpha_{\text{CO}} = 4.35 \times 10^4 \, M_\odot \) (K km s\(^{-1}\) pc\(^{-2}\)) and a 12CO(2–1)/(CO(1–0) line ratio, \( R_{21} = 0.59 \) in K km s\(^{-1}\) units (the most current value for nearby galaxies; den Brok et al. 2021). These new masses are given in Table 2. \( R_{21} \) is relatively well constrained, with uncertainties on average at the <30% level (though they likely vary from galaxy to galaxy). There is also uncertainty in the assumed \( \alpha_{\text{CO}} \) conversion factor. However, Smercina et al. (2018) found good general agreement between (1) the molecular gas masses derived from H\(_2\) pure rotational emission and CO(1–0) using a Galactic CO-to-H\(_2\) conversion, as well as (2) the estimated dust-to-molecular gas ratios of the PSB sample and the dust-to-gas ratios of nearby galaxies—both suggesting that the adopted \( \alpha_{\text{CO}} \) is an appropriate conversion factor for the PSB sample.

Using these newly calculated masses, and our estimates of the spatial scale of the CO emission, we can estimate the PSBs’ molecular gas surface densities. We report the molecular gas surface densities, \( \Sigma_{\text{Mol}} \), within these central cores—noting that in the majority of cases, this captures the majority of the emission (>63% in all but one galaxy; see Table 2).

All six sources possess extremely high central molecular column densities—\( \Sigma_{\text{Mol}} = 344 \times 6.5 \times 10^4 \, M_\odot \, \text{pc}^{-2} \)—the highest of which are consistent with the high inferred dust column densities measured in 0480 and 2777 (Section 3.1). Unlike nearby galaxies, the entire gas reservoirs of these PSBs exist on <1 kpc scales, with surface densities that are therefore orders of magnitude higher than their nearby galaxy counterparts (~300–8 × 10\(^4\) versus ~3–50 \( M_\odot \) pc\(^{-2}\); e.g., Bigiel et al. 2008)—instead rivaling the gas found in the densest compact starbursts (e.g., Kennicutt & De Los Reyes 2021).

### 4. Suppression of Star Formation in a Turbulent ISM

Previous works have compared PSBs’ global SFRs to their global CO emission (French et al. 2015, 2018a; Smercina et al. 2018), making assumptions about the physical scales of each. Without proper measurements of these physical scales, it has not been possible to reliably estimate the quantitative properties of their molecular gas reservoirs, such as the internal turbulent pressure, or how efficiently these reservoirs are forming stars.

In this section, we first estimate the internal turbulent pressure for a subset of our sample, and discuss comparisons to nearby galaxies (Section 4.1), which is followed by an analysis of the suppression of the PSBs’ star formation, relative to the star formation law (Section 4.2).

#### 4.1. Turbulent Pressure

Of the six PSBs studied in this work, three were observed at particularly high physical resolution. The beam sizes for 0480, 0570, and 2360 are only a few hundred parsecs—comparable to the “driving scale” for interstellar turbulence (Brunt 2003),

\[^{16} \text{Including a 1.36 factor for Helium (e.g., Sandstrom et al. 2013).}\]
and approaching the scale of individual giant molecular clouds. The internal turbulent pressure for an individual cloud is proportional to its surface density, $\Sigma$, and line-of-sight velocity dispersion, $\sigma_v$, as $P_{\text{turb}} \sim \Sigma \sigma_v^2$. As the molecular gas is concentrated on scales comparable to the resolving beam, we can estimate $P_{\text{turb}}$ for the "cores" of these three galaxies, with the approximation derived by Sun et al. (2018):

$$P_{\text{turb}} / k_B \approx 61.3 \text{ K cm}^{-3} \left( \frac{\Sigma_{\text{Mol}}}{M_\odot \text{ pc}^{-2}} \right) \times \left( \frac{\sigma_v}{\text{km s}^{-1}} \right)^2 \left( \frac{R_{\text{beam}}}{40 \text{ pc}} \right)^{1},$$

where $\Sigma_{\text{Mol}}$ is the surface density of the molecular core described in Section 3.2.1, $\sigma_v$ is the average velocity dispersion measured in the core, and $R_{\text{beam}}$ is the radius of the beam (averaged over both dimensions) given in Table 2. For the cores of 0480, 0570, and 2360, we estimate log$_{10} P_{\text{turb}}$[K cm$^{-3}$] = 9.8, 9.1, and 8.8, respectively.

One limitation of our observations in drawing inferences about these high turbulent pressures is the possible smearing of high rotational velocities at scales below our physical resolution by the resolving beam. This "beam smearing" can add significant width to the measured velocity dispersion (e.g., see Walter et al. 2022). This a particular concern for sources with considerable rotational velocity signatures, such as 0480. To check the impact of beam smearing on our measured $\sigma_v$, we simulated rotating disks,\footnote{Using the KinMS software package (Python version), written by Timothy Davis (Davis et al. 2013).} comparable in size, shape, and velocity scale to 0480, with several combinations of different intrinsic gas velocity dispersions and rotation curves. We present the full analysis in Appendix C, but summarize the results here. In the case of a steeply declining central component to the rotation curve, such as the presence of a central supermassive black hole, beam smearing could contribute substantially to the measured velocity dispersion at the scale of our observations. However, we find that beam smearing alone, with a much lower velocity dispersion, does not reproduce the observed Moment 2 image or velocity profile well. In the case of 0480 specifically, we find that a somewhat lower gas velocity dispersion of $50 \text{ km s}^{-1}$ (versus $69 \text{ km s}^{-1}$ measured) and a $2 \times 10^4 M_\odot$ central black hole reproduce the observed velocity profile fairly well (see Figure 2). This would imply an overestimation of $P_{\text{turb}}$ of 0.3 dex, reducing it to $10^{9.5} \text{ K cm}^{-3}$—a significant difference, but still much higher than the comparison sample in Figure 5. We conclude that while the observations do indicate much higher than average gas velocity dispersions, they are not high enough in resolution to completely break this degeneracy between smeared rotation from a central point mass and high intrinsic velocity dispersion. We therefore introduce an additional factor of 10 lower uncertainty on $P_{\text{turb}}$, to reflect the possibly significant contribution of beam smearing in our measured velocity dispersions. For context, this would place a lower limit on $\sigma_v$ in 0480 of $40 \text{ km s}^{-1}$, given its measured $69 \text{ km s}^{-1}$. As shown in Figure 5, even if $\sigma_v$ was of order 20–30 km s$^{-1}$ for PSBs, leading to a $10 \times$ overestimation in turbulent pressure, their $P_{\text{turb}}$ values would still be higher than anything besides the Antennae (and higher still for 0480), due to their high surface densities.

In Figure 5, we compare these estimates to the turbulent pressures measured by Sun et al. (2018) in local galaxies, as well as the LIRG NGC 3256 (Brunetti et al. 2021). The turbulent pressure in the three PSBs is 2–3 orders of magnitude higher than the median $P_{\text{turb}}$ measured for gas in the local star-forming disks, and it is $>10 \times$ higher than found in local star-forming nuclei. The closest comparison in the local galaxy sample is the gas in the merging Antennae, which has a median log$_{10} P_{\text{turb}} = 7.9$, and in the late-stage merger NGC 3256, which has a median log$_{10} P_{\text{turb}} = 7.2$ in nonnuclear regions and log$_{10} P_{\text{turb}} = 8.3$ in the nucleus. Even with the possible contribution of beam smearing to their measured velocity dispersions, it is clear: these PSBs' molecular reservoirs are highly turbulent relative to "typical" galaxies, and rival (or even surpass) the turbulent pressures found in late-stage mergers such as the Antennae and NGC 3256. Higher-resolution observations with ALMA should refine these measurements even further, and allow more principled modeling of the rotation curves.

It is interesting to consider the physical interpretation of such high turbulent pressures in nonmerging galaxies. The typical definition of turbulence is that it is part of a true energetic "cascade" down to small physical scales, where it must be accompanied by commensurate dissipation through mechanically heated emission channels. This seems to be at least partially supported by the observed bright pure rotational H$_2$ emission, which is a hallmark of mechanically heated systems (e.g., Altalato et al. 2014; Appleton et al. 2017; Smercura et al. 2018). This scenario would likely favor a physical injection of energy, such as local feedback from AGN activity, active on short enough timescales to counteract the efficient emissive dissipation. The modest outflow observed in the PSB 0637 could be a possible signature of such lower-level current or past AGN activity. However, if feedback alone were the source of turbulent energy injection, we would expect to observe higher-energy cooling lines that are bright enough to dissipate the turbulent energy in the gas. An alternative mechanism is that the apparent turbulent motions represent semicoherent bulk flows of gas on scales smaller than the achieved physical resolution. This effect has been observed in Arp 220, and it is thought to be driven primarily by merger-induced gravitational torques (Scoville et al. 2017). The measured line-of-sight velocity dispersions for these three PSBs range from $\sim 47$–$112 \text{ km s}^{-1}$—very comparable to the velocity dispersions measured in the two nuclei of Arp 220 (Scoville et al. 2017).

It seems most likely that these two mechanisms work in concert. As discussed in Scoville et al. (2017), in the nuclear disks of Arp 220, coherent bulk flows could result in an ISM that is more smooth than the "clumpy" ISM seen in normal galaxies. A largely smooth medium could explain the dearth of high-density molecular tracers, like HCN and HCO\textsuperscript{+} (French et al. 2018b), as it could be simultaneously consistent with the observed H$_2$ rotational emission in PSBs and the lack of optical and IR nebular cooling lines that would typically drive the rapid dissipation of turbulent energy and the fragmentation of the gas. If we assume a very simple model, where the molecular gas in the cores of 0480, 0570, and 2360 is spherically distributed, then we obtain average densities of $n = 10^3$–$10^4$—all below the effective critical density of HCO\textsuperscript{+}, and well below that of HCN (Leroy et al. 2017; Bešlić et al. 2021). If the ISM is as smoothly distributed as such a simple model suggests, then the high surface densities could be entirely consistent with a relative lack of truly "dense gas." It should be noted that dense-gas tracers such as HCN have been observed in Arp 220's nuclei (Barcos-Muñoz et al. 2018), despite a potentially "smooth"
are ordered by increasing the PSBs are shown, incorporating the measured uncertainties on 2022, in preparation information on the state of their ISM densities, and a lack of truly dense gas. Upcoming studies with proposed as a – PSBs is some form of low-level, low – The medians for the local galaxy disks are shown as the gray circles, with the ( described above). In a typical ISM, not ordered in smooth bulk flows, the turbulent dissipation timescale would be roughly the dynamical timescale at the scale of the gas – a few Myr for 0480, 0570, and 2360, assuming their measured velocity dispersions and CO size scales. However, even in a medium with typical nebular cooling lines, although it may take 10 Myr for TDEs to replenish the PSBs’ entire turbulent energy reservoirs, this TDE “duty cycle” could be short enough to counteract the turbulent dissipation of the gas. The second assumption is that the energy produced by the TDE can couple efficiently to the ISM. While this type of “feedback” has not yet been well studied, recent models suggest that the radiative emission, which approximately follows a few × 10⁴ K black-body, may be able to effectively couple to the cold surrounding medium, at least at distances very near the black hole (Bonnerot et al. 2021) — similar to the large scales on which continuous black hole feedback is observed to operate. Though dedicated simulations are required to verify the plausibility of TDEs as a distinct source of black hole feedback, they will be an important mechanism to consider as the field attempts to understand the origin of the turbulent central reservoirs in these PSBs.

4.2. The Star Formation Law

It has been shown previously that these PSBs have low global SFRs (French et al. 2015, 2018a, 2018b; Smercina et al. 2018), and we have shown here that their gas is highly compact and likely turbulent. This is important, as previous studies have found observational and theoretical evidence for the ability of turbulent energy injection to inhibit star formation (Alatalo et al. 2015; Piotrowska et al. 2022). How does the efficiency of the residual star formation in these compact, turbulent reservoirs compare to other known galaxies?

In Figure 6, we compare the surface density of molecular gas (ΣMol) and star formation (ΣSFR) in our PSB sample to the Kennicutt–Schmidt star formation law, taken from normal star-forming and compact IR luminous galaxies (Kennicutt & De Los Reyes 2021). We use the quantities given in Table 2, as well as SFR indicators based on the [Ne II] and [Ne III] mid-IR fine-structure lines, the [C II] 158 μm far-IR cooling line, and the 3–1100 μm TIR luminosity (Smercina et al. 2018). IR SFR tracers are preferred in such dusty, compact systems, as they can penetrate all but the highest columns. Yet, they suffer from their own limitations. All galaxies have a reliable TIR from multiband SED fitting, but the unique radiation fields in PSBs can cause the IR emission to overestimate the current SFR (Hayward et al. 2014; Smercina et al. 2018). The [C II] line, where detected, is similarly limited. Smercina et al. 2018 found [Ne II]+[Ne III] to be the most reliable indicator of the current

18 Similarly, TDE rates are also expected to be high in starburst galaxies (Mattila et al. 2018; Stone et al. 2018), though they are much harder to observe due to obscuration by dust and contamination with AGN emission.
SFR, though these lines are only available for the three galaxies observed with Spitzer InfraRed Spectrograph.

All of the sources are unresolved, and their SFR estimates are global. We therefore assume that star formation activity is spread over the same surface area as the 1.3 mm continuum and CO emission. While star formation may be “clumpy” within the molecular gas region, we do not expect there to be substantial star formation outside of the region of molecular gas emission. We therefore calculate the SFR surface density, $\Sigma_{\text{SFR}}$, identically to $\Sigma_{\text{Mol}}$: by using the size of the resolving beam, which corresponds to the unresolved core of each galaxy, and multiplying by the core fraction, $f_{\text{core}}$.

There are numerous sources of uncertainty (largely systematic) in each of these metrics, and we conservatively estimate them from the measurement uncertainty, the uncertainty in the $\alpha_{\text{CO}}$ conversion factor, and the uncertainties on the measured sizes of the molecular gas and star formation. We do not account for the uncertainty in the different timescales that each indicator likely probes. Rather than fixed points with error bars, we choose to represent these uncertainties as error ellipses in Figure 6, with the width in each direction giving the likely spread in $\Sigma_{\text{Mol}}-\Sigma_{\text{SFR}}$ parameter space. The width of the ellipse in $\Sigma_{\text{Mol}}$ is calculated by adding in quadrature the uncertainties on $L_{\text{CO}(2-1)}$ (see Section 3.3 and Table 2), a 50% uncertainty on the CO size, reflecting the possibility that the gas deviates from a Gaussian distribution as we have assumed, and a conservative 80% uncertainty on the assumed $\alpha_{\text{CO}}$ ($\sim 0.8-7$). The widths in $\Sigma_{\text{SFR}}$ include a 25% uncertainty for a given SFR indicator (following Smercina et al. 2018), a 50% uncertainty on the star-forming size (following the CO), and the spread from the average of the different indicators used.

Even taking into account these uncertainties, Figure 6 demonstrates the very significant suppression of star formation efficiencies of PSBs, relative to galaxies with similar gas densities. Their gas densities are 2–4 orders of magnitude higher than star-forming galaxies with similar global SFRs ($\sim 0.5-5$ $M_\odot$ yr$^{-1}$), yet, despite possessing ULIRG-like surface densities, these reservoirs are forming stars only 10% as efficiently, on average. Coupled with the high $P_{\text{sun}}$ found in Section 4.1, we conclude that turbulent support in the ISM is a likely culprit for this star formation suppression, though it remains unclear over what timescales this turbulent suppression or its driving mechanism could persist.
5. Conclusions

We have presented the results of high-resolution CO(2–1) ALMA observations of six post-starburst galaxies. For the first time, we have resolved the spatial distribution and kinematics of the ISM in this enigmatic class of galaxies. We find:

1. Unresolved, and therefore highly compact, 1.3 mm continuum emission in two galaxies (0480 and 2777). The inferred dust surface densities are extremely high—$\Sigma_d = 3200$ and 527 $M_\odot$ pc$^{-2}$, respectively. These measured dust column densities correspond to visual extinctions of $A_V \sim 2 \times 10^4$ and $\sim 3300$, respectively.

2. Highly compact, largely centrally concentrated molecular reservoirs. The majority of the emission in each source is contained within an unresolved core. The scale of the CO emission is much smaller than in typical star-forming galaxies, both in an absolute sense and relative to the extent of their stellar emission. We derive molecular gas surface densities ranging from 300 $M_\odot$ pc$^{-2}$ to an incredible $7 \times 10^4 M_\odot$ pc$^{-2}$—comparable to those found in the most vigorously star-forming galaxies, such as ULIRGs.

3. A large diversity in morphology and kinematic structure. Some galaxies’ emission is highly patchy, with multiple distinct spatial components, while the gas of others is entirely contained in the core. We see examples of clear rotation in one source, and a possible moderate-velocity outflow in another.

4. Large internal turbulent pressure ($P_{\text{turb}} > 10^8$ K cm$^{-3}$) in the molecular gas of the three galaxies with the highest-resolution observations (0480, 0570, and 2777). Though beam smearing of coherent motions may significantly contribute to the high measured velocity dispersions, the turbulent pressures in these PSBs are at least 2 orders of magnitude higher than found in normal star-forming galaxies, and likely higher even than in nearby mergers, such as the Antennae and NGC 3256.

5. We speculate that a smoothly distributed ISM in these turbulent reservoirs may explain the high gas column densities, yet with the lack of an observed dense-gas tracer emission. We further speculate that the high gas column densities could help to explain the recent finding of particularly high TDE rates in PSBs, through increased orbital drag. We show that these high TDE rates could provide a plausible reservoir of constant energy injection, in the form of low–duty cycle AGN feedback, and could help to explain the high turbulent pressures in such a simple, smooth model ISM lacking typical AGN signatures.

6. Star formation is suppressed by a factor of $\sim 10 \times$ relative to galaxies with comparable gas surface densities. While $\Sigma_{\text{Mol}}$ across the PSB sample is comparable to IR luminous galaxies, $\Sigma_{\text{SFR}}$ is $10 \times$ lower than in their starbursting counterparts. We assert that turbulent heating of these compact reservoirs directly results in this suppression of star formation efficiency.

Our results confirm that the ISM conditions and distributions in these PSBs are unlike normal galaxy populations. Understanding the mechanism driving the turbulent heating of their ISM, and whether this mechanism can maintain the low–star formation efficiency until the remaining gas is consumed, or until it is rendered ineffective for star formation in a future evolutionary state, is of continued importance. The apparently paradoxical states of the gas and the star formation in these unique systems may provide a blueprint for understanding how star formation is quenched and regulated in galaxies “after the fall.”

We thank the anonymous referee for a careful and thoughtful review that improved this paper. A.S. was supported by NASA through grant #GO-14610 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. J.D.T.S. acknowledges visiting support from the Alexander von Humboldt Foundation and the Max Planck Institute für Astronomie. A.M.M. acknowledges support from the National Science Foundation under grant No. 2009416.

This paper makes use of the following ALMA data: ADS/JAO.ALMA# 2015.1.00665.S and 2016.1.00980.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), NSC and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ. We thank the ALMA support staff at NRAO Charlottesville—particularly Sarah Wood and Anthony Remijan—for invaluable help in the reduction and analysis of these observations. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc. Basic research in radio astronomy at the U.S. Naval Research Laboratory is supported by 6.1 Base Funding.

Facility: ALMA .

Software: CASA (McMullin et al. 2007), Matplotlib (Hunter 2007), NumPy (Harris et al. 2020; van der Walt et al. 2011), Astropy (Astropy Collaboration et al. 2018), SciPy (Virtanen et al. 2020), SIOImage DS9 (Smithsonian Astrophysical Observatory 2000), KinMS (Davis et al. 2013).

Appendix A

IR-to-Radio SED for 0480

Figure 7 shows all existing photometry for 0480 from the IR through the radio. The WISE and Herschel SPIRE photometry is taken from Smercina et al. (2018), the ALMA 1.3 mm flux is taken from this work (see Section 3.1), and the radio comes from the VLASS (3 GHz; Lacy et al. 2020) and FIRST (1.4 GHz; Becker et al. 1995) surveys. We also show the best-fit model SED to the IR photometry, following the method of Dale & Helou (2002), applied to the dust models of Draine & Li (2007), and presented in Smercina et al. (2018). The 1.4–3 GHz radio SED is $\sim 2.5 \times$ below the expectation from the radio–IR correlation, given 0480’s inferred TIR luminosity.
The deviation of the ALMA measurement must then be due to an additional emission component, and not due to free–free emission from obscured star formation. Additional radio observations in the ~33 GHz range should provide clarity on the source of this anomalous emission.

Appendix B
Data for Figures 4, 5, and 6
The derived quantities (sizes, velocity dispersions, densities, and turbulent pressures) presented in Figures 4, 5, and 6 are given in Table 3.

| Galaxy | \(R_{50,*}\) | \(R_{50,CO}\) | \(\sigma_v\) | \(\log_{10} \Sigma_{\text{Mol}}\) | \(\log_{10} R_{\text{turb}}\) | \(\log_{10} \Sigma_{\text{SFR,low}}\) | \(\log_{10} \Sigma_{\text{SFR,high}}\) |
|--------|----------|----------|----------|----------------|----------------|----------------|----------------|
| (S18)  | (kpc)    | (kpc)    | (km s\(^{-1}\)) | \(M_\odot \text{ pc}^{-2}\) | \(K \text{ cm}^{-3}\) | \(M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}\) | \(M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}\) |
| 0379   | 2.95     | 0.48     | ...      | 2.57           | ...            | −0.59          | 0.10           |
| 0480   | 1.66     | 0.11     | 69       | 4.85           | 9.8            | 1.59           | 2.78           |
| 0570   | 2.61     | 0.12     | 112      | 3.67           | 9.1            | 0.37           | 1.05           |
| 0637   | 4.57     | 0.72     | ...      | 2.77           | ...            | −0.37          | 0.21           |
| 2360   | 1.55     | 0.15     | 47       | 4.32           | 8.8            | 1.18           | 1.86           |
| 2777   | 3.08     | 0.28     | ...      | 4.46           | ...            | 1.15           | 1.71           |

Note. (1) Galaxy ID. (2) Stellar half-light radius, from SDSS photometry (French et al. 2015; Smercina et al. 2018). (3) CO half-mass radius, estimated from comparing the Gaussian fits to the full gas distributions (see the caption to Figure 4). (4) Average central velocity dispersion, used to calculate \(P_{\text{turb}}\). (5) Molecular gas surface density within the central core of each galaxy. (6) Turbulent pressure calculated from the measured velocity dispersion and the molecular gas surface density, using Equation (3). (7) Lowest estimate on SFR surface density from the three available IR tracers. (8) Highest estimate on SFR surface density from the three available IR tracers.
Appendix C
The Effects of Beam Smearing on Measured Velocity Dispersions

Here we investigate the effect of beam smearing on the measured velocity dispersions in the PSBs. We use 0480 as our standard for this analysis, as it is the only source that exhibits a clear rotational signature in its Moment 1 map and velocity profile. We use the KinMS Python package (Davis et al. 2013) to construct model gas disks similar to 0480, at the same resolution as the observations. Given that we observe rotation, we assume the disks are relatively highly inclined, with inclination $i = 65^\circ$.

We assume an exponential density profile for the gas, of the form $\Sigma \propto e^{-R/R_0}$, with a scale radius $R_0 = 0.15$. For the velocity structure of these model disks, we consider two different rotation curves: (1) a standard rotation curve, $v_{\text{rot}} = (2v_{\text{flat}}/\pi) \arctan(R)$, with $v_{\text{flat}} = 1000$ km s$^{-1}$, and (2) an additional central point-mass component, representing a supermassive black hole with mass $M_{\text{BH}} = 2 \times 10^7 M_\odot$. $v_{\text{flat}}$ was chosen to reproduce the $\sim$150 km s$^{-1}$ velocity difference between the two components in 0480’s velocity profile, which we take as the maximum measured rotational velocity. The black hole mass was chosen assuming that 0480 approximately follows the $M_{\text{BH}} - \sigma_*$ relation (e.g., Gültekin et al. 2009), with $\sigma_* = 124$ km s$^{-1}$ measured by SDSS. We show both of these rotation curves in Figure 8. Last, we consider three different intrinsic gas velocity dispersions, $\sigma_*$, for the disks: (1) 25 km s$^{-1}$, much lower than observed; (2) 69 km s$^{-1}$, matching the average observed dispersion for 0480; and (3) an “intermediate” 50 km s$^{-1}$ dispersion.

We consider five distinct combinations of these rotation curves and intrinsic velocity dispersions: (1) a low-dispersion 25 km s$^{-1}$ model, with a standard rotation curve and no central black hole; (2) a high-dispersion 69 km s$^{-1}$ model, with a standard rotation curve and no central black hole; (3) a low-dispersion 25 km s$^{-1}$ model, with a $2 \times 10^7 M_\odot$ central black hole; (4) a high-dispersion 69 km s$^{-1}$ model, with a $2 \times 10^7 M_\odot$ central black hole; and (5) an intermediate-dispersion 50 km s$^{-1}$ model, with a $2 \times 10^7 M_\odot$ central black hole. In Figure 9, for each of these models, we show the Moment 1 and 2 maps, as well as the extracted velocity profiles. We show 0480’s Moment 2 map and velocity profile for reference. It seems clear from the comparisons that a gas velocity dispersion higher than 25 km s$^{-1}$ is required to reproduce 0480’s Moment 2 map and the shape of its velocity profile, regardless of the presence of a central black hole. Of the five models, the intermediate velocity dispersion of 50 km s$^{-1}$ with a black hole seems to best reproduce the data.

Our data are not of high enough resolution to fully model 0480’s rotation curve and precisely determine the relative contributions of high inner rotation and intrinsic velocity dispersion. It is also possible that additional velocity components, such as compact bars or gas streamers, could contribute to the beam smearing of ordered motions. We can conclude from this analysis that, while beam smearing due to a steep central rotation curve may contribute significantly, it likely cannot account for more than $\sim$50% of the velocity dispersion signal in the source with the clearest rotation. Given the high surface densities and high velocity dispersions, beam smearing thus likely has little impact on our conclusions of high turbulent pressures (i.e., $\log_{10} P_{\text{turb}} > 8$) in the gas of these PSBs.
Figure 9. Moment 1 and 2 maps and velocity profiles for each of the five model disks described in Appendix C. We also show the Moment 2 map of 0480 as an inset in the upper right of each panel in the second column. This is plotted on an identical color scale as the model Moment 2 maps (i.e., 20–100 km s$^{-1}$). Likewise, we show the velocity profile of 0480 (orange) overlaid on the extracted velocity profile for each model (blue).

ORCID iDs
Adam Smercina  https://orcid.org/0000-0003-2599-7524
John-David T. Smith  https://orcid.org/0000-0003-1545-5078
K. Decker French  https://orcid.org/0000-0002-4235-7337
Eric F. Bell  https://orcid.org/0000-0002-5564-9873
Daniel A. Dale  https://orcid.org/0000-0002-5782-9093
Anne M. Medling  https://orcid.org/0000-0001-7421-2944
Kristina Nyland  https://orcid.org/0000-0003-1991-370X
George C. Privon  https://orcid.org/0000-0003-3474-1125
Kate Rowlands  https://orcid.org/0000-0001-7883-8434
Fabian Walter  https://orcid.org/0000-0003-4793-7880
Ann I. Zabludoff  https://orcid.org/0000-0001-6047-8469

References
Alatalo, K., Appleton, P. N., Lisenfeld, U., et al. 2014, ApJ, 795, 159
Alatalo, K., Lacy, M., Lanz, L., et al. 2015, ApJ, 798, 31
Alatalo, K., Lisenfeld, U., Lanz, L., et al. 2016, ApJ, 827, 106
