THE MOLECULAR BARYON CYCLE OF M82

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ABSTRACT

Baryons cycle into galaxies from the intergalactic medium and are converted into stars; a fraction of the baryons are ejected out of galaxies by stellar feedback. Here we present new high-resolution (3′′9; 68 pc) 12CO(2−1) and 13CO(3−2) images that probe these three stages of the baryon cycle in the nearby starburst M82. We combine these new observations with previous 12CO(1−0) and [Fe II] images to study the physical conditions within the molecular gas. Using a Bayesian analysis and the radiative transfer code RADEX, we model temperatures and densities of molecular hydrogen, as well as column densities of CO. Besides the disk, we concentrate on two regions within the galaxy: an expanding super-bubble and the base of a molecular streamer. Shock diagnostics, kinematics, and optical extinction suggest that the streamer is an inflowing filament, with a mass inflow rate of molecular gas of 3.5 M⊙ yr−1. We measure the mass outflow rate of molecular gas of the expanding super-bubble to be 17 M⊙ yr−1, five times higher than the inferred inflow rate and 1.3 times the star formation rate of the galaxy. The high mass outflow rate and large star formation rate will deplete the galaxy of molecular gas within eight million years, unless there are additional sources of molecular gas.

Key words: galaxies: evolution – galaxies: general – galaxies: individual (M82) – galaxies: starburst – ISM: jets and outflows – molecular data

1. INTRODUCTION

Galaxies are not closed systems. Galaxies lose gas by converting a small portion (typically ∼1%) of the gas into stars (Kennicutt 1998; Bigiel et al. 2008; Leroy et al. 2008). A fraction of these newly formed stars are high-mass stars that emit high-energy photons and cosmic rays, and eventually explode as supernovae, which accelerate gas out of the star-forming regions and into a galaxy-scale outflow (Chevalier & Clegg 1985; Heckman et al. 1990, 2000; Veilleux et al. 2005). A portion of this outflow may escape the galactic potential (Heckman et al. 1990; Martin 2005; Rupke et al. 2005; Chisholm et al. 2015), but lower velocity gas recycles back into the galaxy as a galactic fountain (Shapiro & Field 1976). This migration of metal-enriched gas shapes the mass–metallicity relation (Tremonti et al. 2004; Finlator & Dave 2008; Zahid et al. 2014) and enriches the circumgalactic medium with metals (Tumlinson et al. 2011; Peeples et al. 2014; Werk et al. 2014).

Meanwhile, galaxies gain gas through accretion from the circumgalactic medium (Katz et al. 2003; Kereš et al. 2005, 2009; Dekel et al. 2009), as either cold filaments or hot spherical accretion (Kereš et al. 2005; Dekel et al. 2009). Accretion replenishes the gas lost through galactic outflows and star formation, promoting future star formation. Without accretion, galaxies consume their gas within a billion years (Leroy et al. 2008; Genzel et al. 2010).

The baryon cycle is the story of how galaxies acquire, store, and expel baryons. This cycle establishes the star formation history of the universe (Oppenheimer & Davé 2008; Hopkins et al. 2011), the efficiency of star formation (Hopkins et al. 2011), the gas fractions of galaxies (Davé et al. 2011), and the ratio of baryonic to non-baryonic matter within galaxies (Moster et al. 2010).

Mergers and interactions speed up the baryon cycle. During the merger process, gravitational torques strip and compress the gas, increasing the inflow rate (Di Matteo et al. 2005; Springel et al. 2005; Hopkins et al. 2006), the star formation efficiency (Mihos & Hernquist 1994; Saintonge et al. 2012), and the mass outflow rate and velocity of the outflow (Hopkins et al. 2013; Chisholm et al. 2015). This increase in the amount of inflowing and outflowing material makes the baryon cycle easier to detect in merging and interacting galaxies.

M82 is a spectacular nearby (3.6 Mpc; Freedman et al. 1994) starburst that is interacting with the massive spiral M81 (Yun et al. 1993). Due to its proximity, M82 is close enough for us to map the full baryon cycle. Near the center of M82, a starburst with a star formation rate of 13 M⊙ yr−1 (Förster Schreiber et al. 2003) drives a galactic outflow (Lynds & Sandage 1963; Bland & Tully 1988; Shopbell & Bland-Hawthorn 1998) that extends more than 2 kpc from the starburst (Bland & Tully 1988; Shopbell & Bland-Hawthorn 1998; Leroy et al. 2015). This galactic outflow has been observed in hot X-ray-emitting plasma (Griffiths et al. 2000; Strickland et al. 2004; Strickland & Heckman 2009), ionized Hα emission (Lynds & Sandage 1963; Shopbell & Bland-Hawthorn 1998; Ohnaka et al. 2002; Westmoquette et al. 2009b; Sharp & Bland-Hawthorn 2010), and cold molecular gas (Weiß et al. 1999, 2001, 2005; Mao et al. 2000; Matsushita et al. 2000, 2005; Walter et al. 2002; Keto et al. 2005; Salak et al. 2013; Leroy et al. 2015). Since stars form out of molecular gas, the cycle of cold gas into and out of the galaxy characterizes the near-future star formation within galaxies.

Here we trace the baryon cycle of diffuse molecular gas using three 12CO emission lines. In Section 2.1 we describe new high-resolution 12CO(2−1) and 13CO(3−2) images taken with the Submillimeter Array (SMA). We then include previous 12CO(1−0) observations (Section 2.2) and infrared [Fe II] emission maps (Section 3.3) to characterize the physical conditions within the galaxy. The maps of 12CO intensity, velocity, and channels are first presented in Section 3.1, and then we use a Bayesian analysis, with the radiative transfer
code RADEX, to model the temperatures and densities of the molecular gas (Section 3.2).

We focus on three important physical regions within M82: the disk (Section 4.1), the expanding super-bubble (Section 4.2), and the base of a molecular streamer (Section 4.3). Using the derived densities, we measure the masses of each component, and find that the super-bubble has a molecular mass outflow rate of $17 M_\odot$ yr$^{-1}$. In Section 4.3, the kinematics, shock diagnostics, and optical extinction suggest that the molecular streamer is an inflowing filament, with a molecular inflow rate of $3.5 M_\odot$ yr$^{-1}$. Finally, we explore the molecular baryon cycle within M82, finding that the star formation and outflow will consume the molecular gas in eight million years, unless there are extra sources of molecular gas (Section 4.4).

Throughout this paper we assume that M82 is at a distance of 3.6 Mpc (Freedman et al. 1994), and that 1" corresponds to 17.5 pc.

2. DATA AND OBSERVATIONS

Here we describe the observational data sets of M82. We first discuss the new $^{12}$CO(2–1) and $^{12}$CO(3–2) observations (Section 2.1), and then include the $^{12}$CO(1–0) observations from Matsushita et al. (2000) (Section 2.2). In Section 2.3 we introduce the [Fe II] images, which are important shock diagnostics.

2.1. SMA Observations

$^{12}$CO(2–1) observations were taken with the SMA (Ho et al. 2004) on 2004 March 7 and March 12; while $^{12}$CO (3–2) observations were taken on 2005 February 25 (see Table 1). The primary beam sizes of the $^{12}$CO(2–1) and $^{12}$CO(3–2) observations are 55" and 36", respectively. We observe $^{12}$CO(2–1) with one pointing, and mosaic three $^{12}$CO (3–2) pointings to give a similar field of view. The $^{12}$CO (2–1) beam is centered on the central CO peak of M82 (Shen & Lo 1995). The middle $^{12}$CO(3–2) beam is also centered on the CO peak, with the other two pointings separated by 18" (i.e., Nyquist sampled) east and west along the major axis of the disk at a position angle of 75°.

For the data calibration, we use the software package MIR, adopted for SMA. We flag and correct spikes in the system temperature, and make passband calibrations for the phase, amplitude, and gain, and then flux-calibrate the images using the sources listed in Table 1.

We then import the data into the Common Astronomy Software Applications package (McMullin et al. 2007) and combine the individual observations. Using the dirty images, we find line emission in channels between −195 and +150 km s$^{-1}$ (the velocity zero-point here is the velocity of the local standard of rest for M82, 225 km s$^{-1}$), and then subtract the continuum in the UV plane. We clean the continuum-subtracted images to the rms of the dirty image, producing images that oversample the beam (pixel sizes of 0.03 for $^{12}$CO(2–1) and 0.02 for $^{12}$CO(3–2)) and have a velocity resolution of 5 km s$^{-1}$ to match the $^{12}$CO(1–0) observations below. We make a primary beam correction, and integrate intensities that are significant at greater than the $5\sigma$ level to produce zeroth-moment maps. The original spatial resolutions are 3.88 $\times$ 3.32 at a position angle of −26° for $^{12}$CO(2–1) and 2.76 $\times$ 2.23 at −179° for $^{12}$CO(3–2).

Since interferometers incompletely sample the UV plane, we correct for the missing flux with an ad hoc short-spacing correction. The short-spacing correction is made by convolving the zeroth-moment maps to the spatial resolution of previous single-dish observations (Mao et al. 2000; Weiß et al. 2005), and then comparing the intensities within six regions of our interferometric data to the single-dish intensities. The average intensity difference is 49% and 36% for the $^{12}$CO(2–1) and $^{12}$CO(3–2) observations, respectively. We multiply this intensity difference by the number of pixels per beam, and divide by the velocity range integrated over to create the zeroth-moment map. The short-spacing correction is then added to the individual channels. This short-spacing correction only corrects for the average short-spacing. A more robust treatment of the short-spacing corrections would use single-dish data to account for spatial variations in the coverage of the UV plane. In Section 3.1 we compare individual points in our maps of line ratio to single-dish maps, and assign extra uncertainty to the line ratios to account for point-to-point variations. We recreate the zeroth-moment maps, convolve the $^{12}$CO(3–2) map to the resolution of the $^{12}$CO(2–1) map, and convert the intensity into a brightness temperature.

2.2. Nobeyama Millimeter Array (NMA) Observations

The NMA observed M82 in $^{12}$CO(1–0) between 1997 November and 1999 March, and the full reduction details are given in Matsushita et al. (2000). The NMA data have a velocity resolution of 5.2 km s$^{-1}$, a beam size of 21.8 $\times$ 21.3 at −50°, and a pixel size of 0.05°. Similar to the SMA data above, a primary beam correction is made, and a zeroth-moment map is created by integrating between −180 and +150 km s$^{-1}$. We make short-spacing corrections, similar to the $^{12}$CO(2–1) and $^{12}$CO(3–2) maps, with a 9% difference between the single-dish data (Weiß et al. 2005) and the NMA data. Finally, the zeroth-moment map is convolved to the resolution of the $^{12}$CO (2–1) map.

2.3. Hubble Space Telescope (HST) [Fe II] Imaging

We use archival HST [Fe II] 1.6 μm images to determine whether the gas is shocked (Alonso-Herrero et al. 2003). The NICMOS images have a field of view of 53.48 by 66/2 and a resolution of 0.35, more than adequate to compare with the

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Table 1: Calibration Properties

| Line     | Dates       | Bandpass     | Flux       | Gain       |
|----------|-------------|--------------|------------|------------|
| $^{12}$CO(2–1) | 2004 Mar 7   | Callisto     | Callisto   | 0721 + 713 |
|          | 2004 Mar 12  | Ganymede and 3C279 | Ganymede | 0927 + 390 |
| $^{12}$CO(3–2) | 2005 Feb 25  | Callisto     | Callisto   | 0721 + 713 and 0958 + 655 |

Note. Table of the calibrators we use for the data reduction. $^{12}$CO(2–1) has two days of observations, and we list the sources used for both calibrations.

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3 http://www.cfa.harvard.edu/~cqj/mircook.html
CO observations. The images are reduced using the NicRed package (McLeod et al. 1997), flux-calibrated, and continuum-subtracted using off-band F164N images (Alonso-Herrero et al. 2003).

3. RESULTS

Here we present the results of the maps of CO and [Fe II] emission. We first introduce the maps of CO intensity, velocity, position–velocity, channel, and line ratio (Section 3.1). We then model maps of H$_2$ temperature and density using a Bayesian approach (Section 3.2). Finally, we use the [Fe II] emission to locate shocked gas within M82 (Section 3.3).

3.1. Maps of Moment, Channel, and Line Ratio

A zeroth-moment map measures the integrated intensity in each pixel, and the maps for the three CO emission lines are shown in Figure 1. To measure the standard deviation of the zeroth-moment maps, we first measure the standard deviation in the individual channels, then multiply by the velocity resolution (5 km s$^{-1}$) and the square root of the number of channels. The zeroth-moment 1$\sigma$ errors are 103, 55, and 64 K km s$^{-1}$ for the $^{12}$CO(1–0), $^{12}$CO(2–1), and $^{12}$CO(3–2) maps, respectively. Three distinct intensity peaks are seen (Shen & Lo 1995; Weiß et al. 2001; Walter et al. 2002) and four previously observed large-scale features are detected: three molecular spurs off the disk (named S1, S2, S3; Walter et al. 2002) and an expanding super-bubble (Weiß et al. 1999; Matsushita et al. 2000).

The intensity-weighted velocity maps (also called the first-moment maps) are shown in Figure 2. Galactic rotation is seen across the disk, with the velocity increasing steadily from east to west. The rotational center of the galaxy resides between the left two peaks in Figure 1, while an evolved $10^6 M_\odot$ super-star cluster is between the right two CO intensity peaks (Matsushita et al. 2000).

Slicing the image cube along the dashed blue line in the bottom panel of Figure 1, we produce the position–velocity (PV) diagrams for each transition (Figure 2). A PV diagram plots the intensity at a particular position and velocity, and diagnoses the kinematics of the gas. The PV diagrams show a steady decrease in velocity with increasing position (i.e., rigid rotation). Near the 0$^\circ$ position the CO deviates from the rigid rotation. Matsushita et al. (2000) attribute this abrupt change in velocity to an expanding molecular super-bubble.

We also use the channel maps—or the intensity within a given velocity interval—to study the distribution of CO gas in velocity space. Figures 4–6 show the channel maps for $^{12}$CO(1–0), $^{12}$CO (2–1), and $^{12}$CO(3–2), respectively. We define six channels, separated by 55 km s$^{-1}$, with median velocities given in the upper right corners of each map. The $–195$, $–140$, $–30$, and $+80$ km s$^{-1}$ channels largely contain disk emission. The $–85$ km s$^{-1}$ channel (middle left panel) has emission from the super-bubble, and the area defined by this feature is shown by the blue circle in the upper right panel of Figure 1. Moreover, we detect the S2 streamer from Walter et al. (2002) in the upper left corner of the $+25$ km s$^{-1}$ channel (lower left panel). The $^{12}$CO (2–1) and $^{12}$CO(3–2) lines show more streamers: S1 is seen in the bottom right of the $–140$ km s$^{-1}$ channel and in the lower right of the $^{12}$CO(3–2) PV diagram. Additionally, S3 is seen in the bottom left of the $+80$ km s$^{-1}$ channel (bottom left panel). Unfortunately, the sensitivity of the $^{12}$CO(1–0) observations from Matsushita et al. (2000) do not afford detections of these diffuse features.

In Section 3.2 we use the radiative transfer code RADEX and the line ratios to model the temperatures and densities of the molecular gas in M82. Figure 7 shows the $^{12}$CO(2–1)/$^{12}$CO (1–0), $^{12}$CO(3–2)/$^{12}$CO(1–0), and $^{12}$CO(3–2)/$^{12}$CO(2–1) maps of line ratio. Additionally, in Table 3 we tabulate the
CO emission lines for five regions discussed in Section 4. These line ratios provide the basis to model the physical properties of the molecular gas. To calculate the errors on these maps of line ratio we must consider the dominant uncertainties in our calibration procedure, which are the calibration errors (short-spacing corrections), not the statistical uncertainties. Therefore, for the line ratio errors we use a calibration uncertainty of 15% and an uncertainty due to our ad hoc short-spacing correction. We make a point-by-point comparison of single-dish data from Weiß et al. (2005), Wilson et al. (2012), and Leroy et al. (2015) with our line ratios and find a 20% variation. We conservatively attribute this 20% variation to the ad hoc prescription for the short-spacing correction. We then add the short-spacing error in quadrature with the 15% calibration uncertainty to find an uncertainty of 25% on the individual line ratios. This is the uncertainty that we model the temperatures and densities with, below.

3.2. Density and Temperature Modeling

To model the temperatures and densities of the molecular gas, we compare the ratios of the $^{12}$CO(1–0), $^{12}$CO(2–1), and $^{12}$CO(3–2) intensities to theoretical ratios from RADEX (van der Tak et al. 2007). RADEX is a one-dimensional, non-LTE, radiative transfer code that calculates the molecular line ratios using a formulation for the escape probability. RADEX requires inputs of temperature, $H_2$ density ($n_{H_2}$), CO column density ($N_{CO}$), and the FWHM of the CO line. We fit the line widths at each pixel for each transition, and find a median FWHM of 89 km s$^{-1}$. By using the FWHM of the entire galaxy for the RADEX modeling, we assume that the CO-emitting gas is in a single zone, or the entire galaxy is treated as a single cloud of molecular gas. We make this assumption to simplify the Bayesian parameter grid below.

We then create a large grid of RADEX models using the parameters listed in Table 2, and tabulate the predicted line ratios for each input parameter. The RADEX grid is centered on the warm diffuse molecular temperatures and densities found in Weiß et al. (2005), but the grid also allows for very cold dense clouds and the 272 K molecular phase from $H_2$ rotational transitions (Beirão et al. 2015). We use a Bayesian analysis to calculate the probability of each RADEX model given the observed line ratios ($^{12}$CO(2–1)/$^{12}$CO(1–0), $^{12}$CO(3–2)/$^{12}$CO(2–1), and $^{12}$CO
(3–2)/12CO(1–0)), where only locations detected at greater than 1σ, for all three lines, are used. We create probability density functions (PDFs) for each marginalized parameter by assuming a flat prior, such that each value is equally likely, and compute the likelihood function as (Kauffmann et al. 2003; Brinchmann et al. 2004; Feigelson & Jogesh Babu 2012)

\[ L \propto \exp(-\chi^2/2). \]  

(1)

The intensity errors (used in the \(\chi^2\) function) are 25% from the calibration and short-spacing correction (see Section 3.1).
likelihood functions are then normalized, and marginalized over nuisance parameters to produce PDFs for $n_{\text{H}_2}$, temperature, and $N_{\text{CO}}$ individually. The PDFs are typically narrowly peaked and clustered near a single value (see Figure 8), although the temperature PDFs are occasionally broader. The expectation values and standard deviations are calculated from the PDFs. Figure 8 gives a representative example of the three PDFs, the expectation values, and standard deviations from a single pixel within the hot super-bubble region of the $-85 \text{ km s}^{-1}$ channel.

We plot maps of expectation value for the temperature and $n_{\text{H}_2}$ over the entire field of view in Figure 9. Log($n_{\text{H}_2}$) ranges between 1.8 and 3.1 dex, and temperatures range between 61 and 175 K. The median individual standard deviations of the
temperatures and densities are 70 K and 0.66 dex, respectively. Figures 10 and 11 show the temperatures and densities modeled from the channel maps, and reveal the conditions within specific features, such as the super-bubble and S2.

Additionally, we show the relationship between the modeled temperatures and densities (Figure 12). We overplot curves of constant $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(3-2)/^{12}\text{CO}(1-0)$ line ratios from the RADEX models, using a constant $\log(N_{\text{CO}})$ of 19 dex. In Figure 13 we show the curves corresponding to the same constant line ratios, but for a $\log(N_{\text{CO}})$ of 19.3, twice the column density in Figure 12. While both the $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ and $^{12}\text{CO}(3-2)/^{12}\text{CO}(2-1)$ change by changing $N_{\text{CO}}$, the $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ moves to lower temperatures and densities more rapidly than the $^{12}\text{CO}(3-2)/^{12}\text{CO}(2-1)$. This relation allows for low $^{12}\text{CO}(2-1)/^{12}\text{CO}(1-0)$ yet high $^{12}\text{CO}(3-2)/^{12}\text{CO}(2-1)$ ratios seen in the outer bubble and the S2 body to correspond to low $N_{\text{CO}}$ values (see Table 3). This allows for the $N_{\text{CO}}$ values to be modeled by marginalizing over the PDFs.

The RADEX modeling also provides estimates of the optical depth for each transition. In Table 3 we show the optical depth for each transition in five regions that are discussed below. These optical depths are moderately high and consistent with optical depths derived from single-dish data (Leroy et al. 2015). Observations of optically thin tracers could be used in future studies to provide better estimates of the optical depths ($^{13}\text{CO}(1-0)$ for example; see Weiß et al. 2005).

### 3.3. Shocked Gas

$[\text{Fe II}]$ is a forbidden transition and requires densities greater than $10^6$ cm$^{-3}$ to populate the upper energy state (Mouri et al. 1990). Fast $(>100$ km s$^{-1}$) shocks create high temperatures and densities that collisionally excite $\text{Fe II}$, producing $[\text{Fe II}]$ emission in the infrared (Mouri et al. 1990). $[\text{Fe II}]$ is less
susceptible to dust extinction than optical shock tracers (such as [N II]) because of the lower dust attenuation in the infrared. Below, we primarily use these favorable characteristics to determine whether the molecular gas is shocked where S2 intersects the disk.

Figure 14 shows the map of [Fe II] emission. The [Fe II] emission peaks strongly near the center of M82, but the emission also traces the increased density enhancements and depressed temperatures of the super-bubble seen in the $-85 \text{ km s}^{-1}$ channel of Figure 10. Intriguingly, there are knots of emission near the intersection of S2 and the disk (see the green cross in Figure 1 and white crosses in Figure 9 for the approximate location of this feature).

4. DISCUSSION

Here we discuss three intriguing physical regions in the CO observations that probe the three phases of the baryon cycle: (1) the disk (Section 4.1), (2) the expanding super-bubble (Section 4.2), and (3) the base of the S2 molecular streamer (Section 4.3). In each section we describe the region, its derived physical properties, how these properties compare to previous observations, and the mass of the feature. Finally, in Section 4.4 we discuss how the three areas illustrate the baryon cycle within M82.

4.1. The Disk

The molecular disk of M82 is well studied (Weiβ et al. 1999, 2001, 2005; Mao et al. 2000; Matsushita et al. 2000, 2005; Walter et al. 2002; Keto et al. 2005; Salak et al. 2013; Leroy et al. 2015), and here we use our observations to calculate the molecular gas mass of the disk. We define the disk as the area within the $15\sigma$ contours of the $^{12}\text{CO}(2-1)$ intensity map. We make this distinction to avoid contributions from the super-bubble and the molecular streamers, but it affects comparisons with other studies. To compare the total mass directly with previous studies, we also calculate the total mass within the $450 \text{ K km s}^{-1}$ ($\approx 3\sigma$) contours of the $^{12}\text{CO}(1-0)$ map, which accounts for all of the observed CO.

The disk has a mean temperature of $104 \pm 36 \text{ K}$ and log ($n(H_2)[\text{cm}^{-3}]$) of $2.6 \pm 0.5 \text{ dex}$. These values are consistent with values from Weiβ et al. (2001), who use the IRAM Plateau de Bure Interferometer to derive mean temperatures and densities of $125 \pm 50 \text{ K}$ and $3.4 \pm 0.5 \text{ dex}$, respectively.

We calculate the total H$_2$ mass in two ways: (1) by converting the $^{12}\text{CO}(1-0)$ intensity into a total molecular mass using an $X_{\text{CO}}$ factor, and (2) by using the CO column densities ($N_{\text{CO}}$) from the RADEX calculations. Method 1 is primarily used to compare with previous results that use a constant $X_{\text{CO}}$ (Matsushita et al. 2000; Weiβ et al. 2001; Walter et al. 2002), while method 2 uses all three transitions and the radiative transfer analysis to calculate the total H$_2$ mass. We focus on the results from method 2 while discussing the baryon cycle because it incorporates more of the known physics.

Method 1 calculates the total H$_2$ mass as

$$M = X_{\text{CO}} (I_{\text{H}_2})A\bar{m}$$

where $X_{\text{CO}}$ converts the median $^{12}\text{CO}(1-0)$ intensity ($I_{\text{H}_2}$) into an H$_2$ column density, $A$ is the area of the region (in cm$^2$), and $\bar{m}$ is the average mass per H$_2$ molecule (see Table 5). To compare to previous studies (Matsushita et al. 2000; Weiβ et al. 2001; Walter et al. 2002; Keto et al. 2005), we use an $X_{\text{CO}}$ value that is half the Milky Way value (Solomon et al. 1987, Table 5). Using method 1, the total H$_2$ mass within the $3\sigma$ $^{12}\text{CO}$ (1-0) contours is $9 \times 10^8 \text{ M}_\odot$ (see Table 4), similar to the $7 \times 10^8 \text{ M}_\odot$ that Weiβ et al. (2001) and Walter et al. (2002) calculate using the $X_{\text{CO}}$ method.

Method 2 uses the RADEX-derived $N_{\text{CO}}$ to calculate the total H$_2$ mass as

$$M = \frac{N_{\text{CO}}A\bar{m}}{\Delta V Z [\text{CO}]}$$
where $\Delta V$ is the FWHM (89 km s$^{-1}$) and $Z_{[CO]}$ is the CO-to-H$_2$ abundance ratio (see Table 5; Sakamoto 1999). The total molecular gas mass within the field of view is $2.1 \times 10^8 M_\odot$ (see the first row of column 6 in Table 4), similar to the $2.7 \times 10^8 M_\odot$ (Weiß et al. 2001) estimated using an LVG (large velocity gradient) solution.

In the disk, there are $5 \times 10^5 M_\odot$ and $1 \times 10^6 M_\odot$ of H$_2$ using methods 1 and 2, respectively (see Table 4). The two methods differ largely because the excitation of CO depends on the temperature and density of the gas. For example, the $X_{\text{CO}}$ of an optically thick cloud in virial equilibrium scales as $T^{-1.5} n_{H_2}^{1/2}$ (Maloney & Black 1988; Weiß et al. 2001), and high H$_2$ temperatures within the disk decrease the conversion factor (Weiß et al. 2001; Bolatto et al. 2013; Leroy et al. 2015). Higher temperatures excite higher-energy transitions ($^{12}$CO (3–2) for example), causing the $^{12}$CO(1–0) transition to trace a lower fraction of the total H$_2$. This relation holds only for clouds in virial equilibrium, and is meant to illustrate possible ways to decrease $X_{\text{CO}}$. Keto et al. (2005) use high-resolution $^{13}$CO(2–1) observations from the Owens Valley Radio Observatory and this $X_{\text{CO}}$ value to show that the CO clouds are approximately in virial equilibrium, but it is unlikely that all of the diffuse gas (on scales of kiloparsecs) in M82 is in virial equilibrium. To illustrate how the $X_{\text{CO}}$ value changes, we use Equation (1) from Sakamoto (1999) to calculate the $X_{\text{CO}}$ value within the disk as

$$X_{\text{CO}} = \frac{N_{\text{CO}}}{\Delta V Z_{[CO]} \langle J_{10} \rangle}.$$  

(4)

In Figure 15 we find that the median disk value is $4.0 \times 10^{19}$ cm$^{-2}$/(K km s$^{-1}$), roughly consistent with the $X_{\text{CO}}$ factor derived by Weiß et al. (2001) using the LVG method.

**Figure 10.** Maps of density channels with the $^{12}$CO(2–1) contours from Figure 1 overlaid to give a sense of position. The density is displayed only if the three CO lines are detected at a significance level of more than $1\sigma$. The six maps are for the same velocities as Figure 4: $-195$, $-140$, $-85$, $-30$, $+25$, and $+80$ km s$^{-1}$. S2 is seen in the $+25$ km s$^{-1}$ channel (lower left), and the bubble region is seen in the $-85$ km s$^{-1}$ channel (middle left).
However, this $X_{\text{CO}}$ factor is four times smaller than the value assumed in method 1, and almost an order of magnitude lower than the Milky Way value. The total mass is easily overestimated if a constant $X_{\text{CO}}$ factor is assumed, especially in regions with high temperatures and densities.

In summary, we calculate the total H$_2$ mass in two ways: with a constant conversion factor and with our radiative transfer calculations (see Table 4 for the values). Both methods are consistent within a factor of 2 with previous studies. We calculate the $X_{\text{CO}}$ factor within the disk and find that it is also consistent with other studies that use radiative transfer techniques, but it is up to a factor of 4 lower than the constant value typically assumed. We now compare the total H$_2$ mass within the disk to the mass of the starburst-driven super-bubble.

4.2. The Starburst-driven Bubble

The next feature that we discuss is the molecular super-bubble. At the center of the molecular bubble is an evolved $10^6 M_\odot$ super-star cluster dominated by red supergiants. An estimated $4 \times 10^3$ supernovae have exploded throughout the lifetime of the cluster (Matsushita et al. 2000). The energy and momentum from these have created an X-ray-emitting plasma (Griffiths et al. 2000; Matsushita et al. 2005) that expands adiabatically along the minor axis of the galaxy and accelerates the cold molecular gas to velocities that reach $-139 \text{ km s}^{-1}$ (see Figure 3). The maps of the $-85 \text{ km s}^{-1}$ channel (middle left panels in Figures 10 and 11) show that the super-bubble has two components: (1) a shell of moderate density and temperature that traces the [Fe II] emission in Figure 14 and (2) a high-temperature, low-density flow. The temperature and log($n_{\text{H}_2}$[cm$^{-3}$]) in the shell are $82 \pm 17 \text{ K}$ and $2.64 \pm 0.18$ dex, while the warm flow has a temperature of $159 \pm 30 \text{ K}$ and log($n_{\text{H}_2}$[cm$^{-3}$]) of $1.93 \pm 0.15$ dex, significantly warmer and more rarefied than the disk. The dense shell is coincident with the strong [Fe II] emission (Figure 14), indicating that shocks have compressed the H$_2$ to form the dense shell.
Similar to the molecular disk, we calculate the total mass of the bubble in two ways using Equation (2), Equation (3), and the values from Table 4. To calculate the mass of the super-bubble we use the intensity and $N_{\text{CO}}$ found within the $-85 \text{ km s}^{-1}$ channel. This channel maximizes the emission from the bubble while minimizing the contributions from the disk (see Section 3.1). The total mass in the super-bubble is $1.1 \times 10^{8} M_{\odot}$ for method 1. Using a similar $X_{\text{CO}}$ factor, Matsushita et al. (2000) find a total molecular mass of $1.8 \times 10^{8} M_{\odot}$. Using method 2 we find a total $H_{2}$ mass of $1.5 \times 10^{7} M_{\odot}$, 7% of the total $H_{2}$ mass within the galaxy.

We calculate the mass outflow rate using the velocity gradient from the position–velocity diagram (see Figure 3). The bubble initially expands nearly isotropically because it is not pressure-confined by the disk, as shown by the shell-like structure in the PV diagram. This isotropic expansion velocity corresponds to the velocity of the molecular outflow (Matsushita et al. 2000). The velocity gradient ($\nabla$) of the bubble extends from $-85 \text{ km s}^{-1}$ to $0 \text{ km s}^{-1}$, with velocities from $-10$ to $-139 \text{ km s}^{-1}$. Using the conversion factor that $1^\circ$ is $17.5 \text{ pc}$, we calculate $\nabla$ as

$$\nabla = \frac{\Delta v}{\Delta D}$$

with a value of $1.1 \times 10^{-6} \text{ yr}^{-1}$. The total mass outflow rate ($\dot{M}$) is given by

$$\dot{M} = M \nabla$$

for an $\dot{M}$ of $17 M_{\odot} \text{ yr}^{-1}$, using the mass from method 2. We do not calculate $\dot{M}$ for method 1 because of the discrepancies associated with a constant $X_{\text{CO}}$ factor (see Section 4.1).

Interestingly, the molecular mass outflow rate is similar to the large-scale atomic and ionized mass outflow rate calculated using the [O I] and [C II] emission lines (Contursi et al. 2013). However, the molecular, neutral, and ionized outflows are in quite different physical locations; the CO emission dominates the inner kiloparsec of the outflow (Walter et al. 2002; Salak et al. 2013; Leroy et al. 2015), while the neutral and ionized emission extends further into the outflow (Shopbell & Bland-Hawthorn 1998; Leroy et al. 2015). This suggests that the molecular outflow is the base of the galactic outflow. Initially...
Figure 14. HST map of [Fe II] emission, overlaid with white $^{12}$CO(2–1) contours from Figure 1. Knots of [Fe II] emission are near the intersection of S2 (upper left portion of the disk) and along the starburst-driven bubble.

### Table 3

| Feature            | R.A. (2000) hh:mm:ss | Decl. (2000) °   | $^{12}$CO(2–1)/$^{12}$CO(1–0) | $^{12}$CO(3–2)/$^{12}$CO(1–0) | $^{12}$CO(3–2)/$^{12}$CO(2–1) | $\eta_0$ | $\eta_1$ | $\eta_2$ |
|--------------------|----------------------|-----------------|--------------------------------|--------------------------------|--------------------------------|----------|----------|----------|
| Disk               | 09:55:52.4           | +69:40:46.08    | 1.17 ± 0.29                     | 1.10 ± 0.28                     | 0.94 ± 0.24                     | 10       | 36       | 73       |
| Shocked Bubble     | 09:55:51.0           | +69:40:44.82    | 0.62 ± 0.16                     | 0.80 ± 0.2                      | 1.30 ± 0.33                     | 10       | 39       | 79       |
| Outer Bubble       | 09:55:50.9           | +69:40:36.62    | 0.38 ± 0.10                     | 0.33 ± 0.08                     | 0.89 ± 0.22                     | 33       | 120      | 226      |
| Shocked S2         | 09:55:55.4           | +69:40:55.90    | 0.80 ± 0.2                      | 0.78 ± 0.20                     | 0.98 ± 0.25                     | 58       | 194      | 327      |
| S2 Body            | 09:55:56.2           | +69:41:00.00    | 0.59 ± 0.15                     | 0.57 ± 0.14                     | 0.96 ± 0.24                     | 32       | 105      | 176      |

**Note.** Table of CO line ratios for five points in M82. The errors on the line ratios are 25%, as outlined in Section 3.1. The individual points correspond to: the 2 $\mu$m peak position (disk; Lester et al. 1990), a shocked portion of the super-bubble, a position further out in the southern bubble (outer bubble), the location of [Fe II] emission at the intersection of S2 and the disk (shocked S2), and a position in the body of S2. The ratios for the disk are calculated using the maps of integrated intensity, while the bubble and S2 ratios are calculated with only the $\sim$85 and $\sim$25 km s$^{-1}$ channel maps. The final three columns give the RADEX modeled optical depths for the $^{12}$CO(1–0), $^{13}$CO(2–1), and $^{12}$CO(3–2) transitions, respectively.

### Table 4

| Component | A (pc$^2$) | n$_{10}$ (K km s$^{-1}$) | log$_{10}$($^{12}$CO) (cm$^{-2}$) | log$_{10}$(M$_{12}$) 1 (M$_{\odot}$) | log$_{10}$(M$_{12}$) 2 (M$_{\odot}$) | $\nabla$ (10$^{-7}$ yr$^{-1}$) | M (M$_{\odot}$ yr$^{-1}$) |
|-----------|-----------|---------------------------|---------------------------------|-----------------------------------|-----------------------------------|-------------------------------|---------------------------|
| Total     | 395467    | 831                       | 20.10                           | 8.96                              | 8.32                              | ...                          | ...                       |
| Disk      | 137702    | 1199                      | 20.30                           | 8.67                              | 8.06                              | ...                          | ...                       |
| Bubble    | 77388     | 503                       | 19.68                           | 8.04                              | 7.19                              | 10.6                         | 17.1                      |
| S2        | 5650      | 708                       | 19.81                           | 7.41                              | 6.18                              | 9.03                         | 1.4                       |

**Note.** Table of the values used to calculate the total mass of the individual components: the total field of view, the disk, the super-bubble, and the base of the S2 streamer. Column 2 gives the area of each feature (using 17.5 pc per arcsecond), Column 3 gives the average $^{12}$CO column density, calculated with RADEX (see Section 3.2). Column 5 gives the total molecular mass from method 1 (see Equation (2)), and column 6 gives the total molecular mass using method 2 (see Equation (3)). Column 7 gives the velocity gradient derived from the PV diagram (only for the bubble and S2). Column 8 gives the mass outflow (inflow) rate, calculated using the mass from method 2 (column 6). For these calculations we assume a CO-to-H$_2$ abundance ratio of 5 $\times$ 10$^{-5}$ (see Table 5).
the stellar energy and momentum create a hot plasma the size of the star cluster. This hot plasma expands adiabatically and encounters the surrounding dense molecular gas within the disk, shocking and accelerating the molecular gas into the observed shell structure. The hot plasma rapidly heats and dissociates the molecular gas, mixing the cold and hot gas. While the hot outflow initially contains a negligible amount of mass, the added molecular gas significantly increases the mass of the outflow (Chevalier & Clegg 1985; Heckman et al. 1990; Cooper et al. 2008; Strickland & Heckman 2009). This “mass-loading” transports cold gas out of the disk and into the halo through the galactic outflow, where it is later observed through warmer tracers like [O I], [C II], Hα, and metal absorption lines (Heckman et al. 2000; Veilleux et al. 2005; Contursi et al. 2013). Mass conservation requires that the outflow rate at the base of the outflow (the molecular gas) is equal to the outflow rate at later times and larger distances (the neutral and ionized gas), which is consistent with the observations of the atomic and ionized gas.

X-ray emission probes the mass-loading because it arises in the interaction region between the hot plasma and the molecular gas (Strickland & Stevens 2000; Cooper et al. 2008). The mass-loading factor (\( \eta = \dot{M}_g / \text{SFR} \)) measures the efficiency of the outflow relative to the star formation rate. With a star formation rate (SFR) of 13 \( M_\odot \) yr\(^{-1} \) (Förster Schreiber et al. 2003), M82 has a molecular mass-loading factor of 1.3. Models of the X-ray Fe and S line fluxes of M82 find that the mass-loading factor must be between 1.0 and 2.8 (Strickland & Heckman 2009), consistent with the molecular gas mass-loading found here.

After the molecular gas has been ejected from the disk, where does it go? Does the molecular gas have enough kinetic energy to overcome gravity or will the gas fall back as a galactic fountain (Shapiro & Field 1976)? The two scenarios illustrate very different implications for the baryon cycle: recycled gas can eventually be retained as stars, while escaping gas will decrease the fraction of baryons relative to the dark matter. Using a conservative estimate that the escape velocity is three times the circular velocity (Heckman et al. 2000) and a circular velocity of 136 km s\(^{-1} \) (Yun et al. 1993), the escape velocity of M82 is 408 km s\(^{-1} \), significantly higher than the CO outflow velocity of 139 km s\(^{-1} \) from Figure 3. However, dissociated clouds of CO can be accelerated by ram pressure, and the clouds may then approach the escape velocity. Chisholm et al. (2016) find a shallow scaling relation between SFR and the centroid velocity of the Si IV absorption lines (a tracer of warm ionized gas). Using 13 \( M_\odot \) yr\(^{-1} \), these scaling relations predict the Si IV velocity would be 222 km s\(^{-1} \), implying that the molecular gas must accelerate by 87 km s\(^{-1} \) during the dissociation and ionization process. However, this velocity is still below the escape velocity, and the molecular gas is likely recycled. This result echoes the finding from Leroy et al. (2015) where the radial density profiles of the gas and dust are too steep to produce a galactic outflow. The steep density profiles more naturally suggest that M82’s molecular bubble ends as a galactic fountain rather than a large-scale outflow.

### 4.3. The Bases of the Molecular Streamers

Walter et al. (2002) identify four “streamers” in the wide-field CO images. These streamers are large-scale structures that extend 2 kpc from the edge of the molecular disk (Salak et al. 2013; Leroy et al. 2015). While we detect S1 and S3 in the 12CO(2–1) and 12CO(3–2) images, the 12CO(1–0) field of view only provides adequate analysis of the base of the S2 streamer (the northeastern streamer). However, S2 is the base of a large H I trailing tail thought to have formed from the interaction of M82 and M81 (Yun et al. 1993, 1994). The S2 streamer has the highest H I column density of the observed streamers (5.6 \( \times 10^{20} \text{ cm}^{-2} \)), and an estimated H I mass of 6.4 \( \times 10^7 \text{ M}_\odot \) (Yun et al. 1993).

S2 is set apart from the disk as a region of moderately high density and temperature in the full temperature and density plots (Figure 9). In the +25 km s\(^{-1} \) channel map (lower left panel of Figure 11), S2 has a log(\( n(H_2)(\text{cm}^{-3}) \)) of 2.3 dex and a temperature of 128 K. The kinematics of S2 also distinguish it from the disk, with S2 blueshifted \( -37 \text{ km s}^{-1} \) from the disk (see Figure 2).

Further, in Section 3.3 we find that there is a strong knot of [Fe II] at the intersection of S2 and the disk, demonstrating that the gas is shocked at their intersection. The [Fe II] is not the only shock tracer available. Westmoquette et al. (2009a) find elevated [N II]/Hα and [S II]/Hα ratios near the base of S2, but caution that the elevated ratios could be due to hydrogen absorption. Finally, García-Burillo et al. (2001) find that the two main sources of SiO in M82 are the super-bubble and the “chimney,” a large extended filament out of the disk. Figure 2 of García-Burillo et al. (2001) shows a third source of SiO emission northeast of the main chimney, at a position and velocity consistent with the intersection of S2 and the disk. SiO traces shocked gas because it is released after a shock destroys...
dust grains (Martin-Pintado et al. 1992). Therefore, the available shock diagnostics indicate that there is a shock at the intersection of S2 and the disk.

The distinct kinematics of S2 suggest that it is either an inflowing molecular filament or a molecular outflow. These two scenarios are distinguished by the geometries of the system: if S2 is on the far side, the blueshifted emission implies that the gas is flowing onto the disk; whereas if S2 is on the near side, the blueshifted emission implies that the gas is flowing out of the disk. Three observations lead us to hypothesize that S2 is an inflowing filament. First, if S2 is a molecular outflow there should be a burst of star formation that drives the CO out of the disk. There is not strong emission at 100 GHz (Matsushita et al. 2005), Hα (Westmoquette et al. 2009a), Paα (Alonso-Herrero et al. 2003), nor X-rays (Griffiths et al. 2000) in this region, implying that there is not a large amount of star formation in the vicinity. Second, there are strong shock indicators at the intersection of S2 and the disk. Gas flowing into a rotating disk will shock, but CO flowing out from the disk would not. Third, using the N\textsubscript{CO} column density measured along S2, the CO-to-H\textsubscript{2} conversion factor, and a Calzetti extinction law (Calzetti et al. 2000), we would expect S2 to extinguish the galaxy by an AV of 28 mag, which is not observed in optical images of S2 (Mutchler et al. 2007). Therefore, we assume that S2 is on the far side of the galaxy and that it is a molecular inflow. In fact, S2 is likely the base of the large-scale gaseous streamer observed in H\textsc{ii} that is created through the tidal interactions between M82 and M81 (Yun et al. 1993, 1994).

To calculate the mass inflow rate of molecular gas, we use the area defined by the kinematically distinct region of the 12CO(2–1) velocity map (see the velocity map in Figure 2, and Figure 1 for the blue outline of the region). The total molecular gas mass of the base of S2, using method 1 (Equation (2)), is $3 \times 10^9 M_\odot$, while the molecular gas mass is $2 \times 10^6 M_\odot$ using method 2 (Equation (3)). The velocity gradient is measured from the PV diagram and found to be $9 \times 10^{-7} \text{yr}^{-1}$ for a total mass inflow rate of molecular gas of $1.4 M_\odot \text{yr}^{-1}$ (see Table 4).

Here, we only observe the molecular accretion, but there are other contributions to the total baryon cycle in M82. M82 gains and loses neutral and ionized gas, while dissociation, ionization, and recombination convert the molecular, neutral, and ionized gas into other phases. This leads to a fluid, and complicated, inflow rate. Furthermore, the accretion we probe is only filamentary, and mostly due to the tidal interaction with M82’s companions. Spherical accretion assuredly occurs in many of the phases. Unfortunately, spherical accretion is difficult to distinguish kinematically from disk gas because the velocities of both are set by the gravity of the galaxy. Therefore, the accretion rate we measure is a lower limit to both the molecular accretion rate and the total accretion rate.

4.4. The Molecular Baryon Cycle

In the last three subsections we have outlined how gas is accreted onto the nearby starburst M82 (Section 4.3), resides within it (Section 4.1), and is ejected out of it (Section 4.2). Additionally, baryons can be locked into stars through star formation, and M82 is forming stars at a rate of $13 M_\odot \text{yr}^{-1}$ (Förster Schreiber et al. 2003). This traces the entire molecular baryon cycle. To remain in a steady state, M82 requires a molecular inflow rate of $30 M_\odot \text{yr}^{-1}$ (SFR plus $M$), but we observe a molecular inflow rate of only $1.4 M_\odot \text{yr}^{-1}$ from one molecular streamer—out of the four known.

Yun et al. (1993) find that the S2 streamer contains 40% of the observed H\textsc{i} mass in the streamers. If we assume that the H\textsc{i} is a proxy for the H\textsc{ii} and that the other streamers accrete onto the disk at the same relative rate as S2, the total inferred molecular inflow rate is $3.5 M_\odot \text{yr}^{-1}$ ($1.4 M_\odot \text{yr}^{-1}/0.4$). Using this accretion rate, we find that M82 is consuming and expelling molecular gas nine times faster than it is acquiring it. The molecular baryon cycle in M82 is running a deficit: if the current rates continue, M82 will consume or expel all of the observed molecular gas in 7.8 Myr. With over $3 \times 10^8 M_\odot$ of H\textsc{i} in and around the galaxy (Yun et al. 1993), converting H\textsc{i} into H\textsc{ii} may extend this depletion timescale (Krumholz et al. 2008, 2009), but how efficiently H\textsc{i} is converted into H\textsc{ii} is uncertain. Additionally, ionized gas can recombine and eventually cool to molecular gas, and spherical accretion of ionized gas may provide another source of molecular gas. However, if the acquisition rate of molecular gas does not increase in the next 8 Myr, the star formation rate or the outflow rate must decrease, or M82 will exhaust all of its molecular gas.

5. Conclusion

We present 12CO(2–1) and 12CO(3–2) observations of M82, a nearby starburst galaxy. We combine these measurements with previous 12CO(1–0) and [Fe II] emission lines to illustrate the physical properties of the molecular gas. We calculate the molecular gas mass of three previously identified features: the disk, an expanding super-bubble, and the base of a molecular streamer (named S2). Using the kinematics, shock tracers (SiO emission and [Fe II] emission), and optical extinction, we argue that S2 is an inflowing filament of molecular gas that is shocked as it encounters the disk. We then compare the star formation rate (13 $M_\odot \text{yr}^{-1}$), molecular mass outflow rate (17 $M_\odot \text{yr}^{-1}$), and molecular mass inflow rate (3.5 $M_\odot \text{yr}^{-1}$) to find that the molecular gas is consumed more rapidly than it is replenished by the inflow. We conclude that the baryon cycle in M82 is running a deficit: unless more molecular gas is acquired, the star formation rate or outflow rate must decrease in the next eight million years.

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