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MID-INFRARED SPECTROSCOPY OF CANDIDATE ACTIVE GALACTIC NUCLEI-DOMINATED SUBMILLIMETER GALAXIES

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Molecular Gas in a Submillimeter Galaxy at $z=4.5$: Evidence for a Major Merger at 1 Billion Years after the Big Bang¹

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ABSTRACT

We report the detection of CO molecular line emission in the $z=4.5$ millimeter-detected galaxy COSMOS-J100054+023436 (hereafter: J1000+0234) using the IRAM Plateau de Bure interferometer (PdBI) and NRAO's Very Large Array (VLA). The $^{12}\text{CO}(4-3)$ line as observed with PdBI has a full line width of $\sim 1000 \text{ km s}^{-1}$, an integrated line flux of $0.66 \text{ Jy km s}^{-1}$, and a CO luminosity of $3.2 \times 10^{10} L_{\odot}$. Comparison to the 3.3σ detection of the CO(2-1) line emission with the VLA suggests that the molecular gas is likely thermalized to the J=4-3 transition level. The corresponding molecular gas mass is $2.6 \times 10^{10} M_{\odot}$ assuming an ULIRG-like conversion factor. From the spatial offset of the red- and blue-shifted line peaks and the line width a dynamical mass of $1.1 \times 10^{11} M_{\odot}$ is estimated assuming a merging scenario. The molecular gas distribution coincides with the rest-frame optical and radio position of the object while being offset by

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0.5" from the previously detected Ly α emission. J1000+0234 exhibits very typical properties for lower redshift ($z\sim 2$) sub-millimeter galaxies (SMGs) and thus is very likely one of the long sought after high redshift ($z>4$) objects of this population. The large CO(4-3) line width taken together with its highly disturbed rest-frame UV geometry suggest an ongoing major merger about a billion years after the Big Bang. Given its large star formation rate (SFR) of $> 1000 M_{\odot} yr^{-1}$ and molecular gas content this object could be the precursor of a 'red-and-dead' elliptical observed at a redshift of $z=2$.

Subject headings: galaxies: formation – galaxies: high-redshift – galaxies: ISM – galaxies: starburst – submillimeter

1. Introduction

Wide field blank sky surveys at millimeter and sub-millimeter wavelengths have established a population of active star forming galaxies at high redshift (e.g. Blain et al. 2002). These sources or so-called submillimeter galaxies (SMGs) dominate the (sub-)millimeter background, and represent (50-75)% of the star formation at high redshift causing a significant revision to the optically derived star formation history of the Universe (Smail et al. 1997; Hughes et al. 1998; Barger et al. 1998; Bertoldi et al. 2000).

The bulk of this population lies at redshifts below $z=3$, with far-infrared (FIR) luminosities of $\geq 10^{13}L_{\odot}$, which (if powered by star-formation) imply star-formation rates in excess of $1000 M_{\odot} yr^{-1}$. This is sufficient to build up the stellar mass of a giant elliptical galaxy in about 1 Gyr (Chapman et al. 2005). At redshifts $z\leq 3$ about 100 SMGs are now known, many of which have been studied in detail, including CO observations that indicate that they are very massive systems (Greve et al. 2005). Recent high resolution studies of the molecular gas in $z\sim 2-3$ SMGs (Tacconi et al. 2006, 2008) showed that the star forming regions are fairly compact and that the SMGs resemble "scaled-up and more gas-rich versions" of the local Ultra-Luminous Infra-Red Galaxies (ULIRGs; e.g. Downes & Solomon 1998). Due to their derived central densities, which are close to those of ellipticals or massive bulges, they appear to form stars at the maximal rate over very short time scales ("maximum starburst"). Thus the SMGs phase appears to last for about 100 Myr (Tacconi et al. 2008). These massive starburst galaxies place tight constraints on galaxy formation models (e.g. Baugh et al. 2005). One major focus of current and future (sub-)mm surveys is to identify these massive starbursts at $z>3$, a redshift range for which SMGs could place tight constraints on hierarchical merger vs. monolithic collapse models in galaxy formation scenarios.

The discovery of such an SMG above a redshift of $z=4$ indicates that massive galaxy formation is already well under-way when the universe is only 1.5 Gyr old. The recently discovered object J1000+0234 originally selected as a V band drop-out with a weak radio counterpart (Carilli et al. 2008) and with a stellar mass of $M_* > 10^{10} M_\odot$, a young starburst age of 2-8 Myr and a star formation rate of $\text{SFR} > 1000 M_\odot \text{yr}^{-1}$ is a candidate for such a $z>4$ SMG, as it was detected in its FIR continuum (Capak et al. 2008). Throughout this paper we assume a standard concordance cosmology ($H_0 = 70, \Omega_M = 0.3, \Omega_\Lambda = 0.7$).

2. Observations

The bolometer camera MAMBO-2 at the IRAM 30m telescope was used in on-off mode in December 2007 and January 2008 to measure the 1.2 mm flux density of J1000+0234. The weather conditions during the observations were good, the reduction was performed using MOPSIC (written by R. Zylka, IRAM). The achieved rms for a total on-sky integration of 70 min is 0.67 mJy. J1000+0234 was detected at a 5σ level with a total 1.2mm continuum flux density of 3.4 mJy.

The $^{12}\text{CO}(4-3)$ line tracing cold molecular gas in J1000+0234 was observed with the IRAM Plateau de Bure interferometer (PdBI) between January and April 2008 in the special C and C configurations. Both receivers were tuned to the redshifted line frequency of 83.3257 GHz covering a total bandwidth of ~ 0.9 GHz. For calibration and mapping, we used the standard IRAM GILDAS software packages CLIC and MAPPING (Guilloteau & Lucas 2000). The quasar 1005+058 was used for atmospheric calibration while standard calibrators were used for flux calibration. The 12 hr of total integration time result in a data cube of $2.3'' \times 1.9''$ resolution (using robust weighting) with an rms of $0.42 \text{ mJy beam}^{-1}$ for 20 MHz ($\sim 72 \text{ km s}^{-1}$) wide channels.

We used the VLA in D configuration to observe the $^{12}\text{CO}(2-1)$ line in June and July 2008 for a total of 21 hr. The two 50 MHz wide correlator units (each corresponding to a velocity width of $\sim 360 \text{ km s}^{-1}$) were tuned to 41.6352 GHz (on-line) and 41.7351 GHz (off-line). The observations were done in the fast-switching mode using the nearby quasar 1018+055, at a distance of 5.3° from our source, for atmospheric amplitude and phase calibration. 20 antennas were available during the observations and the phase stability was typically $\sim 10^\circ$. The final images using natural weighting have a resolution of $1.9'' \times 1.4''$ and an rms of $49 \mu\text{Jy beam}^{-1}$.

All observed and derived properties of J1000+0234 are summarized in Tab. 1.

3. The Molecular Gas Properties

The CO(4-3) line was detected at a 5.5σ level (Fig. 1) in a 280 MHz wide channel, which corresponds to a full line width at zero intensity (FWZI) of $\sim 1000 \text{ km s}^{-1}$, i.e. with an integrated flux of $0.66 \text{ Jy km s}^{-1}$. The peak position of the CO(4-3) emission (see Fig. 2) agrees very well within the positional uncertainties with the rest-frame near-IR and radio position derived by Capak et al. (2008). The line emission of CO(4-3) is centered at an observed frequency of 83.1857 GHz, which corresponds to a redshift of $z=4.5423$ (assuming a rest frequency of 461.040768 GHz for $^{12}\text{CO}(4-3)$). Given the large line width this is in agreement with the optically derived redshift of $z=4.547\pm 0.002$ (Capak et al. 2008). The CO(4-3) emission coincides with the rest-frame optical counterpart (as traced by the IRAC data) of J1000+0234 (Fig. 2). Averaging the remaining channels blue- and redwards of the detected line emission results in a line-free image of 620 MHz width ($\sim 2200 \text{ km s}^{-1}$) with a tentative 2.2σ detection of the continuum at the rest-frame optical/radio position of the source (Fig. 1).

The VLA observations with a channel width of $\sim 360 \text{ km s}^{-1}$ are centered at the middle of the line detected in CO(4-3). CO(2-1) line emission is detected at the 3.3σ level and coincides spatially with the CO(4-3) emission within its positional uncertainties of $\text{FWHM}_{beam}/(S/N)\sim 0.5''$. Only about a third of the total line width was covered during the VLA observations, so the detected line flux of $0.057 \text{ Jy km s}^{-1}$ could be higher by a factor of ~ 3 , taking the missed blue- and redshifted emission into account by assuming a box-car line shape. The ratio of the CO(4-3) line flux of $0.66 \text{ Jy km s}^{-1}$ to the thus corrected CO(2-1) line flux of $\sim 0.16 \text{ Jy km s}^{-1}$ is about 4, implying that the molecular gas is still thermalized at the J=4-3 transition, as the flux still increases with ν^2 at this transition.

Continuum emission from J1000+0234 was detected at 1.2 mm at $(3.4\pm 0.67) \text{ mJy}$, while the off-line channels in the interferometric observations resulted in a 3σ upper limit of $150 \mu\text{Jy}$ at 41.7 GHz (VLA) and a tentative 2.2σ detection of $(0.17\pm 0.08) \text{ mJy}$ at 83.3 GHz (PdBI). All these values are consistent with the SED fits presented by Capak et al. (2008)¹ and a dust temperature of 30 - 50 K, typically found in $z\sim 2$ SMGs (Pope et al. 2006; Kovács et al. 2006).

¹The scaling of the SEDs presented in Fig. 4 of Capak et al. (2008) is overestimated by a factor of 10^9 (P. Capak, priv. comm.).

4. Masses and Typical SMG Properties

As the molecular gas appears to be thermalized at least up to the CO(4-3) transition as inferred above, its line flux can be used to estimate the CO luminosity [setting $L'_{\text{CO}}(\text{J} = 4 - 3) = L'_{\text{CO}}(\text{J} = 1 - 0)$] and hence the molecular gas mass present in J1000+0234. To derive the CO luminosity L'_{CO} and molecular gas mass M_{gas} we use equations 3 and 4 from Solomon & Vanden Bout (2005) with a conversion factor for L'_{CO} to M_{gas} of $\alpha = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$ derived for local ULIRGs (Downes & Solomon 1998) and used for high redshift objects (Solomon & Vanden Bout 2005). The observed line flux of $S_{\text{CO}(4-3)} = 0.66 \text{ Jy km s}^{-1}$ corresponds to a CO luminosity of $L'_{\text{CO}} \sim 3.2 \times 10^{10} L_{\odot}$ or a molecular gas mass of $M_{\text{gas}} \sim 2.6 \times 10^{10} M_{\odot}$.

We imaged the red and blue ($\approx 500 \text{ km s}^{-1}$ wide) halves of the line emission separately, resulting in a 4.7σ (red) and 3.8σ (blue) emission peak, respectively. The two peaks (Fig. 3) show a spatial shift of $\sim 1''$ roughly from northwest to southeast (with a positional uncertainty of $\sim 0.5''$). This offset corresponds to $\sim 6.6 \text{ kpc}$ at the redshift of J1000+0234, suggesting that the CO emission might be fairly extended. Using this spatial offset between the red- and blue-shifted half of the line emission and the line width of $\sim 1000 \text{ km s}^{-1}$, we can estimate the dynamical mass of J1000+0234. We use the relation between dynamical mass M_{dyn} , velocity width $\Delta v_{\text{FWHM}} = v_{\text{rot}}(r) \times \sin i / 2.4$ and radial extent r of the CO emitting region: $M_{\text{dyn}} \times \sin^2 i = 4 \times 10^4 r \Delta v_{\text{FWHM}}^2$ (Neri et al. 2003). As the system is likely merging (as discussed below) we include also a factor of 2 for a merging system assuming that the gas has already settled into the new potential (Genzel et al. 2003). The estimated dynamical mass of J1000+0234 is about $1 \times 10^{11} M_{\odot}$ for values of $v_{\text{rot}}(r) \times \sin i \sim 1000 \text{ km s}^{-1}$ and a radius r of 3.3 kpc . Thus J1000+0234 has a gas fraction of $M_{\text{gas}}/M_{\text{dyn}} \sim 25\%$, typical for SMGs (Greve et al. 2005; Tacconi et al. 2006). We would like to caution that the derived offset of $\sim 1''$ has significant uncertainties and thus the derived dynamical mass could be overestimated if the separation were smaller.

The properties of J1000+0234 are very similar to the global properties derived for $z \sim 2$ SMGs in terms of molecular gas mass ($\langle M_{\text{gas}} \rangle \sim 3 \times 10^{10} M_{\odot}$), extent ($r_{\text{CO}} \sim 2 \text{ kpc}$), CO line width ($\langle \text{FWHM}_{\text{CO}} \rangle \sim 780 \text{ km s}^{-1}$), dynamical mass ($\langle M_{\text{dyn}} \rangle \sim 1.2 \times 10^{11} M_{\odot}$) and molecular gas mass fraction ($\sim 25\%$) (Greve et al. 2005). Its estimated current gas consumption time scale of $\tau = M_{\text{gas}}/\text{SFR} \approx 30 \text{ Myr}$ assuming our gas mass and a SFR of $\geq 1000 M_{\odot} \text{ yr}^{-1}$ (Capak et al. 2008) is similar to the gas depletion rates of $\sim 100 \text{ Myr}$ found for the $z \sim 2$ SMGs (Tacconi et al. 2008). Taking together the stellar mass of $\geq 10^{10} M_{\odot}$ produced in a recent burst $\sim 7 \text{ Myr}$ ago (Capak et al. 2008) and the available gas reservoir and gas consumption time scale derived here, a significant fraction of the stellar mass of a massive elliptical could be produced on a relatively short time scale. Assuming that these

recently formed stars will be passively evolving since then, J1000+0234 could turn into a ‘red-and-dead’ elliptical – like those that are found at $z=2$ when about 2 Gyr have passed since $z=4.5$.

5. Evidence for an Ongoing Major Merger

The molecular gas emission arises from a region that is highly obscured at the observed optical wavelengths (see Fig. 1 of Capak et al. 2008, Fig. 2 and 3). However, it is coincident with the position of the rest-frame optical and radio emission (Fig. 2). The HST ACS image of J1000+0234 (Capak et al. 2008) was adaptively smoothed (Scoville et al. 2000) to enhance the structure present in the blue continuum covered by the F814W filter (Fig. 3). The molecular gas appears to lie next to bright blue continuum emission that is at its eastern side. $\text{Ly}\alpha$ emission has also been associated with this bright rim in blue continuum (Capak et al. 2008). The motion of the gas is roughly along a region of higher extinction (compared to the blue western component) running roughly from north to south and shows a larger spatial extent than the blue continuum emission. Note the object west of the gas emission is a foreground galaxy at $z=1.41$. As already mentioned by Capak et al. (2008) this geometry is very reminiscent of an ongoing merger. As the redshift of the molecular gas is very close to the redshift derived from the $\text{Ly}\alpha$ line ($z=4.542$ vs. $z=4.547$), it is very likely that both components belong to the same (highly disturbed) system. Both the large FWZI of the CO(4-3) line and the appearance of J1000+0234 in $\text{Ly}\alpha$ make an ongoing merger scenario very likely. We derive a conservative estimate of the merging time for J1000+0234 of significantly less than a billion years using the prescription of Kitzbichler & White (2008) for close galaxy pairs with velocities of $v < 3000 \text{ km s}^{-1}$. This time scale is consistent with having a relaxed system at a redshift of $z=2$.

The expected number of $z=4-5$ SMGs from the model of Baugh et al. (2005) yields of the order of 10-20 such sources within the 2 deg^2 COSMOS field. As J1000+0234 was originally identified as a Lyman Break Galaxy via its V-band drop (Capak et al. 2008; Carilli et al. 2008), this suggests that UV emission can be detectable from ongoing major mergers at these redshifts. We have identified 4 additional V-band dropout LBGs with 4σ radio detections (Carilli et al. 2008) that could also be SMGs at this redshift. An inspection of their optical appearance in the HST ACS data shows that two of them also have a disturbed geometry. This suggests that there could be more objects sharing properties of both the SMG and LBG population at $z>4$ and J1000+0234 might therefore provide an important link between the SMG and LBG populations at high redshifts.

The case of J1000+0234 shows that (at least some) $z>4$ SMGs can have very similar

properties to their well-studied low redshift ($z \sim 2$) counterparts, that major mergers with very large SFRs are likely present at $z=4.5$ and that these systems might be the precursors of elliptical galaxies found at the red sequence at a redshift of $z=2$.

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Facilities: IRAM (PdBI,30M), NRAO (VLA)

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Table 1. Properties of J1000+0234

Property	Value	Comment
$S_{250\text{ GHz}}$ [mJy]	3.4 ± 0.67	MAMBO
$S_{83\text{ GHz}}$ [mJy]	0.2 ± 0.09	off-line channels ($\sim 2\sigma$, PdBI)
$S_{42\text{ GHz}}$ [mJy]	≤ 0.15	off-line channel ($\leq 3\sigma$, VLA)
$z_{\text{CO}(4-3)}$	4.542	center of CO(4-3) line
$\text{FWZI}_{\text{CO}(4-3)}$ [km s $^{-1}$]	~ 1000	CO(4-3) line
$S_{\text{CO}(4-3)}$ [Jy km s $^{-1}$]	0.66 ± 0.12	5.5σ detection (PdBI)
$S_{\text{CO}(2-1)}$ [Jy km s $^{-1}$]	$0.057 \pm 0.017^\dagger$	3.3σ detection* (VLA)
R.A. $_{\text{CO}(4-3)}$ (2000)	10:00:54.484	line peak
Dec. $_{\text{CO}(4-3)}$ (2000)	+02:34:35.73	line peak
L'_{CO} [L_\odot]	3.2×10^{10}	from CO(4-3)
M_{gas} [M_\odot]	2.6×10^{10}	from CO(4-3)
$M_{\text{dyn}} \times \sin^2 i$ [M_\odot]	1.3×10^{11}	using FWZI & $r=0.5''$

Note. — Some properties measured from our PdBI and VLA data and derived using the equations given by Solomon & Vanden Bout (2005) and Neri et al. (2003).

† observed line flux not corrected for small bandwidth (see text for details)

* available bandpass corresponds to $\Delta v \approx 360$ km s $^{-1}$, i.e. a third of the total line width

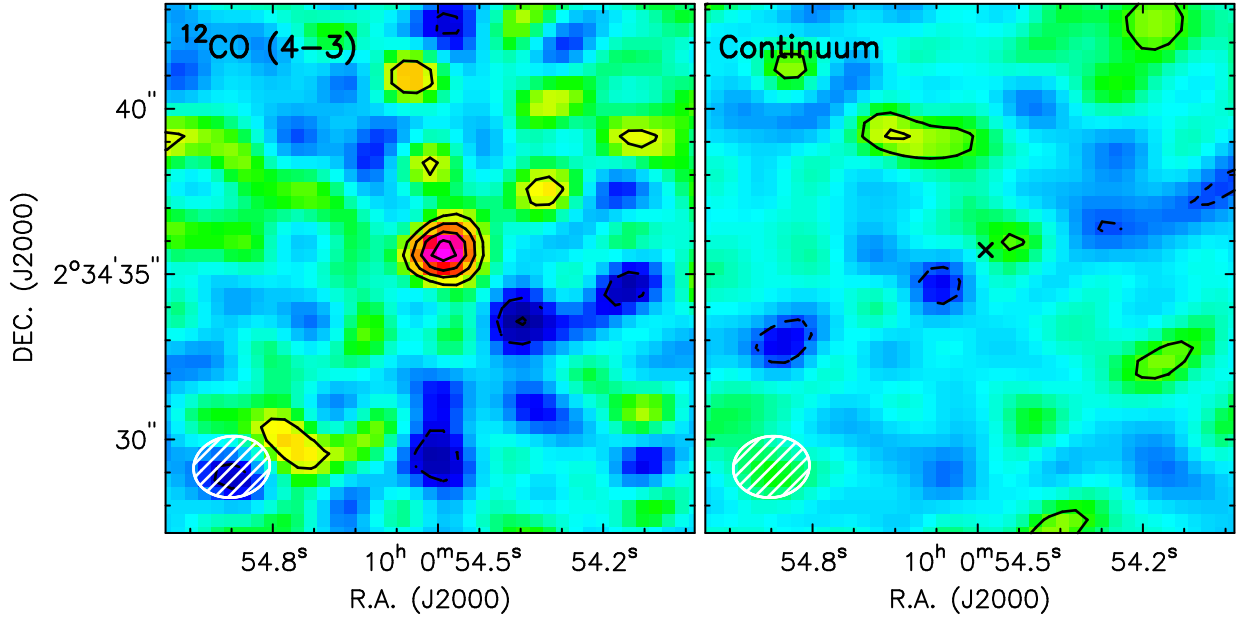


Fig. 1.— CO(4-3) line emission and corresponding continuum in J1000+0234 as observed with the PdBI, shown on the same color scale, but with different contour levels. Continuum emission from J1000+0234 is detected at the 2σ level, while the emission from the CO(4-3) line shows a solid detection at 5.5σ . The integrated CO(4-3) line emission (*left*) is centered at a velocity of $+500 \text{ km s}^{-1}$ relative to the observed frequency of 83.3257 GHz. Contours start at 2σ in steps of 1σ with $1\sigma = 0.12 \text{ Jy beam}^{-1} \text{ km s}^{-1}$. The integrated continuum (*right*) has the same contour steps, however 1σ corresponds to 0.08 mJy/beam . The cross indicates the position of the CO(4-3) peak. The beam is shown in the lower left corner.

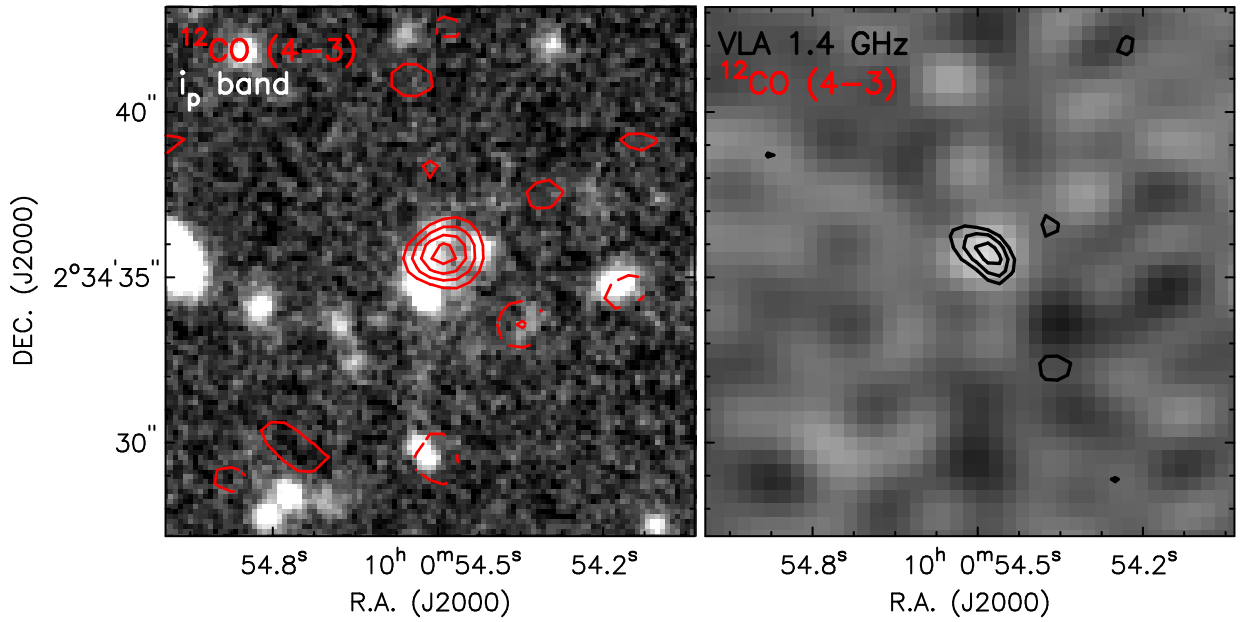


Fig. 2.— Location of the molecular gas relative to other tracers. *Left*: The CO(4-3) line intensity overlaid in contours (same as in Fig. 1) on the Subaru i_p band image, showing an offset from the bright blue continuum rim. *Right*: VLA 1.4 GHz continuum contours (65% to 95% of the maximum of $45\mu\text{Jy}$; Schinnerer et al. 2007) overlaid onto the CO(4-3) map showing an excellent correspondence between the molecular gas and the radio continuum, which is presumably tracing star formation activity.

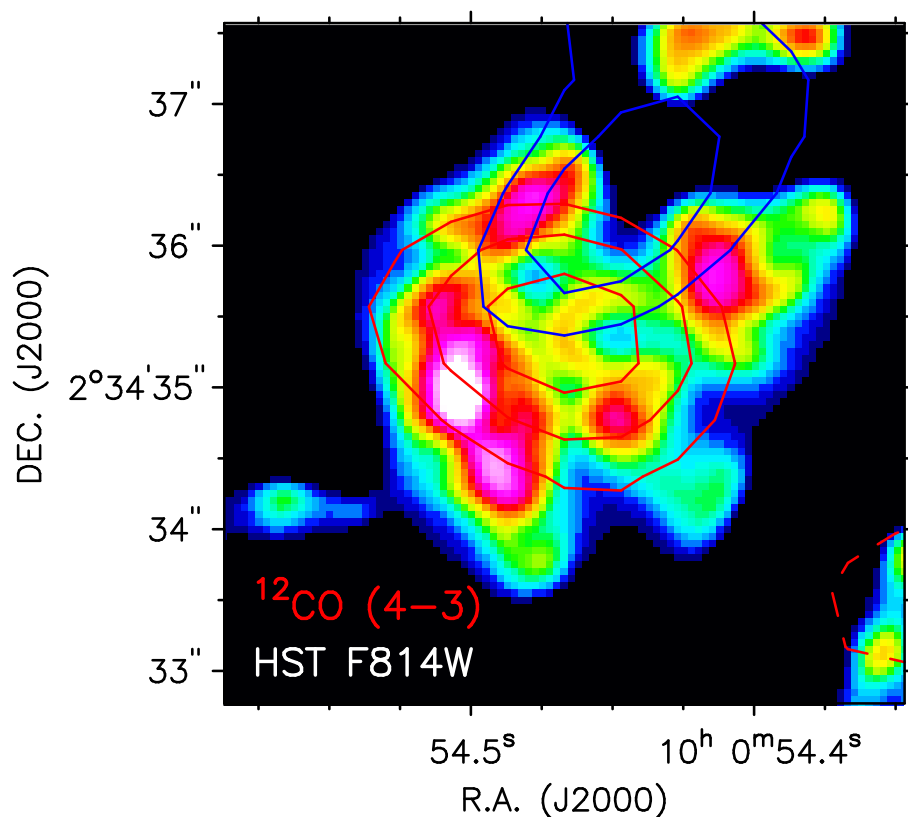


Fig. 3.— Integrated red- and blueshifted CO(4-3) line emission in contours overlaid on the adaptively smoothed HST ACS/F814W image of J1000+0234. A motion from southeast to northwest is apparent with an offset of $\sim 1''$ between the peaks of the red- and blueshifted emission. The contours start at 2σ in steps of 1σ with $1\sigma = 0.085 \text{ Jy beam}^{-1} \text{ km s}^{-1}$ and $0.084 \text{ Jy beam}^{-1} \text{ km s}^{-1}$ for the red- and blueshifted line emission, respectively. The object $\sim 0.5''$ west of the CO emission is a foreground galaxy at $z=1.41$ (Capak et al. 2008).