

This is not yet a paper. It is a collection of paper ideas and some preliminary analysis that will make it in to one or more papers.

Data summary: the 7m and 12m data have all been delivered, but the UV coverage is non-optimal. Importantly and unfortunately, no single-dish (total power) data were ever acquired. I have been granted APEX time using the new PI230 instrument to recover the spectral line zero spacings, and that data is likely to be acquired in October or December. The original proposed project connecting cloud scales to core scales will not be possible until the single dish data are acquired.

Subprojects:

1. Core identification and mass estimation and maybe even core mass function constraints. Lead: Ginsburg. This document is a quasi-draft of that work.
2. "A multi-phase outflow from a high-mass protostar" The Lacy jet is detected in both CO and RRLs. This tells us something about its proximity to the HII region IRS2, but what else can we learn from it? Lead: maybe Ginsburg. Maybe this gets incorporated into other papers.
3. Comparative chemistry of the W51 cores. Lead: Victor Rivilla & Maite Beltrán, possibly with participation from Alvaro Sanchez-Monge. This project will involve identifying all of the lines in the W51 cores and examining how the chemistry relates to physical parameters. We will use LTE modeling tools (XCLASS, MAD-CUBA) for many species to identify lines and determine abundances and temperatures **Discuss with Victor & Alvaro: Can the moderate-mass cores be chemically distinguished from the high-mass? Do we know their masses well enough now to do this?**
4. H₂CO and CO turbulent cloud modeling / simulation comparison (Loughnane). A difficulty here is that combination of the 7m and 12m data has not worked out very well yet, either for the lines or the continuum, and that may render cloud-scale analysis quite difficult.
5. A study of the CO outflows. Lead: Maybe Luke Maud? Ciriaco Goddi will be involved. The ¹²CO and SO outflows are spectacular and plentiful. It is not obvious whether they can or should be incorporated into this paper; at least, I am not presently prepared to put in the effort to quantify the outflows properly. Ciriaco is PI of a long-baseline program that has resolved the e2/e8 and North cores with 5× better resolution than this program, and that data set may therefore be better suited to a core-outflow association work.
6. Relative kinematics of ionized and molecular gas. Lead: Galván-Madrid. Kinematics similar to ? using RRLs+molecular lines to determine outflow vs infall

1. Overview

This section is not part of any proposed paper text. The work below will be incorporated into one or more papers as it proves useful. The figures & text represent an initial exploration of the data. There are some important notes that are not included in the text:

- The data reduction has some substantial problems because of strange UV coverage and stranger behavior of clean (for which I have opened many tickets). It appears impossible to get the noise below ~ 1 mJy around the

bright sources, and detections are unreliable below ~ 10 mJy in these area (which I've tried to account for when doing source extraction)

- The 7m data does not combine well with the 12m data. It seems to cause major large-angular-scale artifacts. I think this is a weighting issue in which the 7m data have lower noise than the 12m data and are therefore too heavily weighted, causing large "halos" where the large angular scale dominates over the small, providing spuriously strong detections. In principle, this can be solved by downweighting the 7m data, but it turns out CASA does not have that implemented (`innertaper` is the relevant keyword)

2. Observations

As part of ALMA Cycle 2 program 2013.1.00308.S, we observed a $\sim 2' \times 1'$ region centered between W51 IRS2 and W51 e1/e2 with a 37-pointing mosaic. Two configurations of the 12m array were used, achieving a resolution of $0.2''$. Additionally, a 12-pointing mosaic was performed using the 7m array, probing scales up to XXX'' . The full UV coverage was from XX to YY m.

Data reduction was performed using CASA. The QA2-produced data products were combined using the standard inverse variance weighting (check this). The visibilities were imaged into full spectral cubes at coarse ($0.5''$) resolution in order to get a first look at all 15630 spectral channels. The resulting cube was used to identify bright lines in the spectrum extracted from source e8. To produce continuum images, frequency channels including bright lines were excluded.

The spectral setups were ...

2.1. Data Reduction

2.1.1. Continuum

A continuum image combining all 4 spectral windows was produced using `tclean`. We phase self-calibrated the image on baselines longer than 100m to increase the dynamic range. The final image was cleaned with 50000 iterations to a threshold of 5 mJy. The lowest noise level in the image, away from bright sources, is ~ 0.2 mJy/beam, but near the bright sources e2 and IRS2, the noise reached as high as ~ 2 mJy/beam. Deeper cleaning was attempted, but lead to instabilities.

2.1.2. Lines

We produced spectral image cubes of the lines listed in Table

2.1.3. UV coverage

2.2. Continuum Morphological Analysis

The largest detected structures include the W51 Main HII region bubble and the W51 IRS2 HII region, which are relatively uninteresting since their properties have been previously well-characterized using radio (JVLA) data. More exciting are the bright dusty structures, especially the "tail" pointing south of W51 e8, which can be described as a 0.25

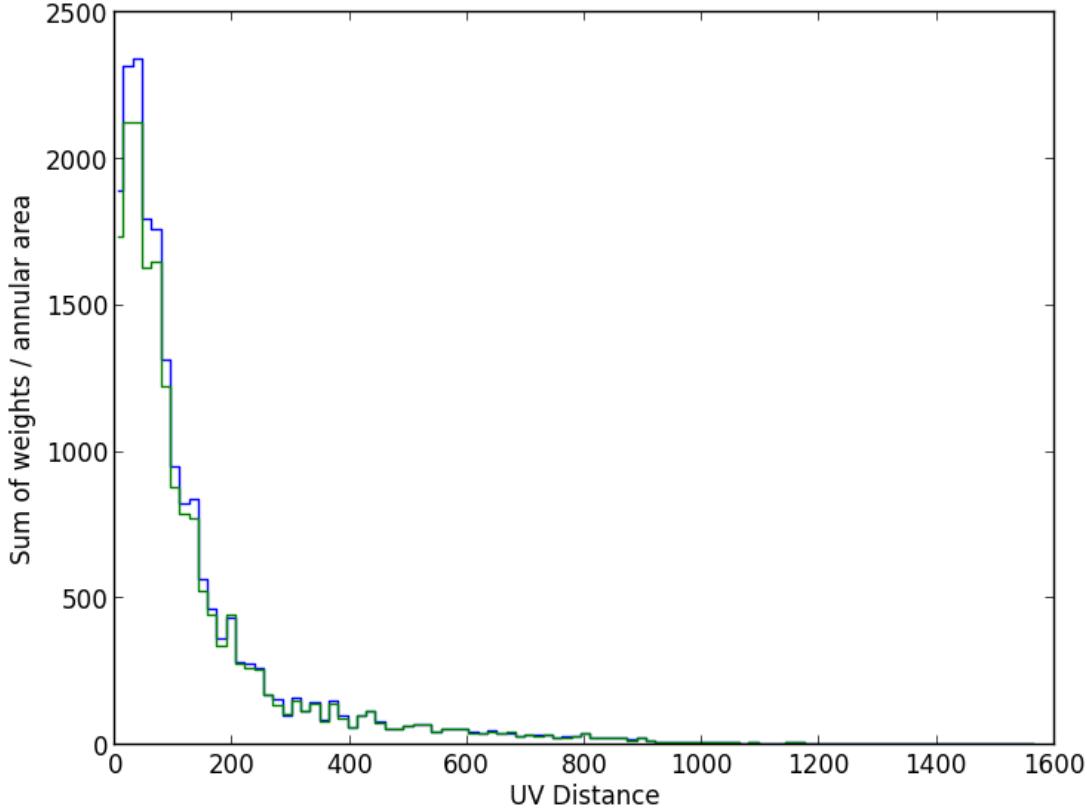


Fig. 1. A weighted histogram of the visibility weights as a function of UV distance; this approximately shows the amount of data received at each baseline length.

pc by 0.05 pc filament. This structure has a very high surface brightness along its ridge, exceeding 40 mJy/beam in our TE maps (23 K or 3.7×10^4 MJy sr $^{-1}$). This high brightness implies a high intrinsic temperature, $T > 30$ K (Section 3.5).

This narrow filament is most prominent in the continuum. It is evident in some lines (H_2CO , ^{13}CS , C^{18}O), but not others (SO ,). It is surrounded by molecular emission that is only slightly fainter... ...in SO it's pretty uniform brightness...

2.2.1. A bubble around e5

There is evidence of a bubble in the continuum around e5 with a radius of $6.2''$ (0.16 pc; Figure 2). The bubble is completely absent in the centimeter continuum, so the observed emission is from dust. The bubble edge can be seen from 58 km s^{-1} to 63 km s^{-1} in C^{18}O and H_2CO , though it is not continuous in any single velocity channel. There is a collection of compact sources (protostars or cores) along the southeast edge of the bubble.

The presence of such a bubble in dense gas, but its absence in ionizing gas, is surprising. The most likely mechanism for blowing such a bubble is ionizing radiative feedback, especially around a source that is currently a hyper-compact HII region, but since no free-free emission is evident within or on the edge of the bubble, it is at least not presently driving the bubble. A plausible explanation for

this discrepancy is that e5 was an exposed O-star within the past Myr, but has since begun accreting heavily and therefore had its HII region shrunk. This model is marginally supported by the presence of a ‘pillar’ of dense material pointing from e5 toward the south.

The total flux in the north half of the ‘bubble’, which shows no signs of free-free contamination, is about 1.5 Jy. The implied mass in just this fragment of the bubble is about $M \sim 350 M_\odot$ for a relatively high assumed temperature $T = 50$ K. The total mass of the bubble is closer to $M \sim 1000 M_\odot$, though it may be lower ($\sim 500 M_\odot$) if the southern half is dominated by free-free emission.

With such a large mass, the implied density of the original cloud, assuming it was uniformly distributed over a 0.2 pc sphere, is $n(\text{H}_2) \approx 2 - 5 \times 10^5 \text{ cm}^{-3}$.

To evaluate the plausibility of the HII-region origin of the bubble, we compare to classical equations for HII regions. The Strömgren radius is

$$R_s = \left(\frac{3Q_H}{4\pi\alpha_B n^2} \right)^{\frac{1}{3}}. \quad (1)$$

For $Q_H \sim 10^{49} \text{ s}^{-1}$, $\alpha_B = 3 \times 10^{-13} \text{ cm}^3 \text{s}^{-1}$, $R_s \approx 0.01 \text{ pc}$.

The Spitzer solution for HII region expansion gives

$$R_{\text{HII}}(t) = R_s \left(1 + \frac{7}{4} \frac{c_{\text{II}} t}{R_s} \right)^{\frac{4}{7}}. \quad (2)$$

With $c_{\text{II}} = 7.5 \text{ km s}^{-1}$ and $t = 10^4 \text{ yr}$, $R_{\text{HII}}(t) \approx 0.04 \text{ pc}$, while at $t = 10^5 \text{ yr}$, it is $R_{\text{HII}} \approx 0.16 \text{ pc}$, which is comparable to the observed radius ($r_{\text{obs}} \sim 0.13 - 0.19 \text{ pc}$)

Whitworth et al. 1994 give the fragmentation timescale as

$$t_{\text{frag}} \sim 1.56 \left(\frac{c_s}{0.2 \text{ km s}^{-1}} \right)^{\frac{7}{11}} \left(\frac{Q_{\text{H}}}{10^{49} \text{ s}^{-1}} \right)^{-\frac{1}{11}} \left(\frac{n}{10^3 \text{ cm}^{-3}} \right)^{-\frac{5}{11}}$$

Plugging in our numbers gives $t_{\text{frag}} \approx 1.0 \times 10^5 \text{ yr}$, or 10× longer than the expansion time.

These values are consistent with a late O-type star having been exposed, driving an H II region, for $\sim 10^4 - 10^5$ year, after which a substantial increase in the accretion rate quenched the ionizing radiation from the star, trapping it into a hypercompact ($r < 0.005 \text{ pc}$) configuration. The recombination timescale is short enough that the ionized gas would disappear almost immediately after the continuous ionizing radiation source was hidden. This is essentially the scenario laid out in ? as an explanation for the compact H II region lifetime problem. In this case, however, it also seems that the H II region has effectively driven the “collect” phase of what will presumably end in a collect-and-collapse style triggering event.

Technically, it is possible that e5 actually represents an optically thick high-mass-loss-rate wind rather than an ultracompact HII region, but I think we can rule this out on physical plausibility considerations if we compare to wind models. Note that η Car would have a flux of $\sim 0.5 \text{ Jy}$ at 2 cm and $\sim 5 \text{ Jy}$ at 1 mm at the distance of W51.

2.3. Dense Gas Kinematics

We examine the gas kinematics throughout the cloud, but especially near the massive cores.

The ambient cloud, which consists of gas that has not yet condensed into compact prestellar objects, is evident in absorption against the mm cores at $55-58 \text{ km s}^{-1}$ (toward e2) and $57-60 \text{ km s}^{-1}$ (toward e8). Narrower velocity components related to the known high-velocity streams are detected around 68 km s^{-1} toward both sources. These absorption features are seen in all H₂CO transitions, CH₃OH $4_{2,2} - 3_{1,2}$, OCS 18-17, but it was less obvious or absent in HNCO $10_{1,10} - 9_{1,9}$ and OCS 19-18.

In the material surrounding the e2 and e8 “cores”, one particularly notable feature is that the cores themselves show a redshifted centroid velocity relative to their surroundings in nearly all of the bright lines (H₂CO, OCS, SO, C¹⁸O). The observed shift is up to $\lesssim 2 \text{ km s}^{-1}$. The shift is a sign of infall. Given the high continuum brightness, the cores are likely optically thick in the continuum (Section ?? XXX), therefore obscuring all molecular emission behind them. We are seeing only gas in the foreground, and this gas is clearly moving toward the cores.

The source ALMAmm14 shows a similar kinematic signature....

3. Analysis

3.1. Source Identification

We used the `dendrogram` method described by ? and implemented in `astrodendro` to identify sources. We used a

minimum value of 1 mJy/beam ($\sim 5 - \sigma$) and a minimum $\Delta = 0.4 \text{ mJy/beam}$ ($\sim 2 - \sigma$) with minimum 10 pixels (each pixel is $0.05''$). This cataloging yielded over 8000 candidate sources, of which the majority are noise or artifacts around the brightest sources. To filter out these bad sources, we created a noise map taking the local RMS of the `tclean`-produced residual map over a $\sigma = 30 \text{ pixel}$ ($1.5''$) gaussian. We then removed all sources with peak S/N < 8 , mean S/N per pixel < 5 , and minimum S/N per pixel < 1 . We also only included the smallest sources in the dendrogram, the “leaves”. These parameters were tuned by checking against “real” sources identified by eye and selected using `ds9`: most real sources are recovered (but not all; see Section ...) and few spurious sources (< 10) are included. The resulting catalog includes 113 sources.

The ‘by-eye’ core extraction approach, in which we placed `ds9` regions on all sources that look ‘real’, produced a more reliable but less complete (and less quantifiable) catalog. This catalog is more useful in the regions around the bright sources e2 and north, since these regions are affected by substantial uncleansed PSF sidelobe artifacts. In particular, the dendrogram catalog includes a number of sources around e2/e8 that, by eye, appear to be parts of continuous extended emission rather than local peaks; “streaking” artifacts in the reduced data result in their identification despite our threshold criteria.

When extracting properties of the ‘by-eye’ sources, we used variable sized circular apertures, where the apertures were selected to include all of the detectable symmetric emission around a central peak up to a maximum radius $r \sim 0.6''$. This approach is necessary, as some of the ‘cores’ are not centrally peaked and are therefore likely to be starless cores.

3.2. The spatial distribution of cores

The detected cores are not uniformly distributed across the observed region. The most notable feature in the spatial distribution is their alignment: most of the cores are detected along common lines. This is especially evident in W51 IRS2, where the core density is very high and there is virtually no deviation from the line. The e8 filament is also notably linear, though there are a few sources detected just off the filament.

On a larger scale, the e8 filament points toward e2, apparently tracing a slightly longer filamentary structure. With some imagination, this might be extended along the entire northeast ridge to eventually connect in a broad half-circle with the IRS2 filament (Figure 3). This morphology hints at a possible sequential star formation event, where some central bubble has swept gas into these filaments. However, this ring has no counterparts in ionized gas, and there is little reason to expect such circular symmetry from a real cloud, so the star forming circle may be merely a figment.

Whether it is physical or not, there is a notable lack of cores within the circle. There is no lack of molecular gas, however, as both CO and H₂CO emission fill the full field of view.

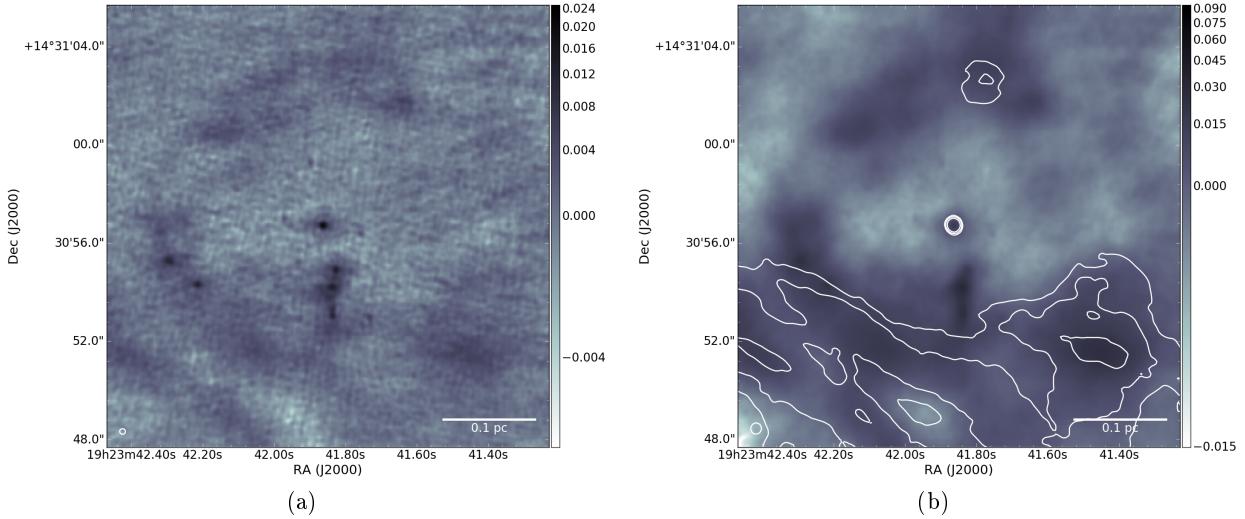


Fig. 2. The bubble around source e5. The bubble interior shows no sign of centimeter emission, though the lower-left region of the shell - just south of the “cores” - coincides with part of the W51 Main ionized shell. The source of the ionization is not obvious. (*Left*): A robust -2.0 image with a small ($0.2''$) beam and poor recovery of large angular scale emission. This image highlights the presence of protostellar cores on the left edge of the bubble and along a filament just south of the central source. (*Right*): A robust +2.0 image with a larger ($0.4''$) beam and better recovery of large angular scales. The contours show radio continuum (14.5 GHz) emission at 1.5, 3, and 6 mJy/beam. While some of the detected 1.4 mm emission in the south could be free-free emission, the eastern and northern parts of the shell show no emission down to the $50 \mu\text{Jy}$ noise level of the Ku-band map, confirming that they consist only of dust emission.

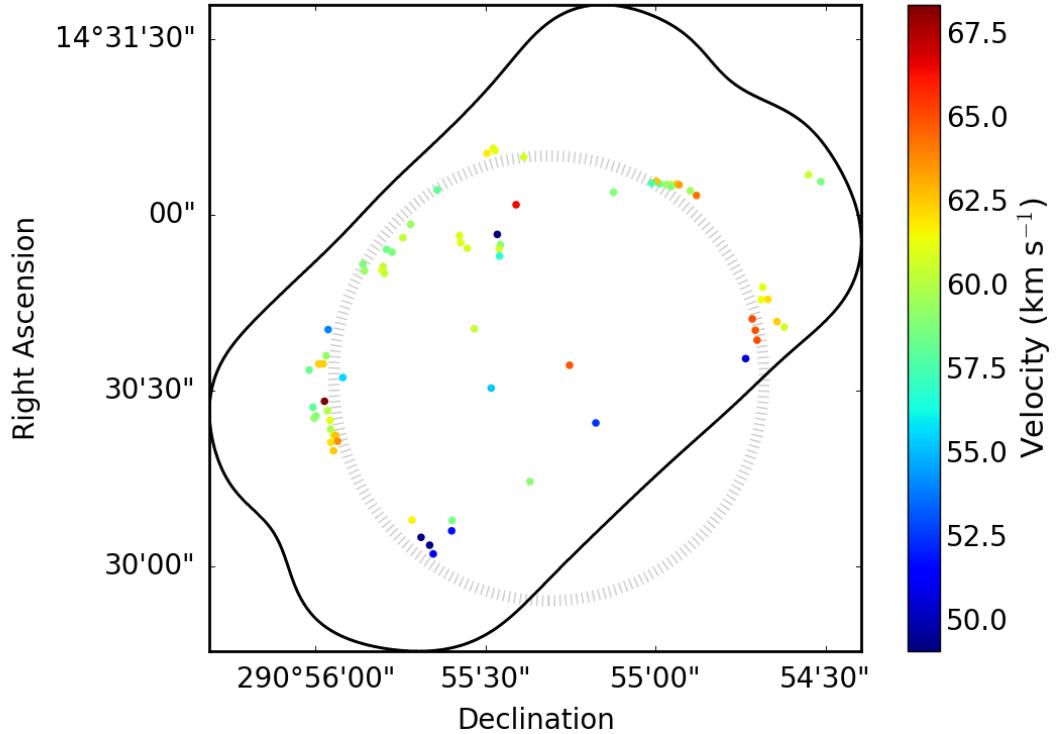


Fig. 3. The spatial distribution of the hand-identified core sample. The black outer contour shows the observed field of view. The dashed circle shows a hypothetical ring of star formation.

3.3. Photometry

We created a catalog of the dendrogram sources including their peak and mean flux density, their centroid, and their geometric properties. For each source, we further extracted

aperture photometry around the centroid in 6 apertures: 0.2, 0.4, 0.6, 0.8, 1.0, and $1.5''$. We performed the same aperture photometry on the W51 Ku-band images from ?. These observations are reported in Table

The source flux density distribution is shown in Figure 4. The most common nearest-neighbor separation between cataloged cores is $\sim 0.3''$, which implies that the larger apertures double-count some pixels. The smallest separation is $0.26''$, so the $0.2''$ aperture contains only unique pixels.

3.3.1. Distribution Functions

We fit power law distributions to each aperture's flux distribution using the packages `plfit` and `PowerLaw` (<https://github.com/keflavich/plfit>, <https://github.com/jeffalstott/powerlaw>; ??). The power-laws steepen slightly from $\alpha = 2.0 \pm 0.12$ to $\alpha = 2.2 \pm 0.16$ for larger apertures. The minimum flux density represented by a power law increases from ~ 20 mJy for the peak flux density distribution to 0.4 Jy for the largest aperture ($14\text{--}280 M_{\odot}$ at 20K). These slopes are shallower than the Salpeter-like slope for the mass function derived by (?) for their sample, though with only modest significance ($< 3 - \sigma$). Of course, these measurements are of the continuum flux density, not directly of the mass, and so a direct comparison may not be appropriate. We revisit this question after assessing the dust temperature in Section 3.5.

3.4. Spectral Lines & Velocities

To determine the line-of-sight velocity of each source, we extracted a spectrum from an $0.5''$ aperture centered on the source and from a $0.5\text{--}1.0''$ annulus around it. We then searched each spectrum for the brightest pixel and associated it with the likeliest spectral line. We repeated this in each of our 4 spectral windows, then averaged the 4 velocities to get an estimate of the source velocity. This process also allowed us to identify the brightest lines in each window and the brightest overall line observed, which we use later for temperature estimation.

3.5. Temperature estimation of the continuum sources

The temperature is a critical ingredient for determining the total mass of each continuum source or region. Since we do not have any means of directly determining the dust temperature, as the SED peak is well into the THz regime and inaccessible with any existing instruments at the requisite resolution, we employ alternative indicators. Above a density $n \gtrsim 10^5 - 10^6 \text{ cm}^{-3}$, the gas and dust become strongly collisionally coupled, meaning the gas temperature should accurately reflect the dust temperature. Below this density, the two may be decoupled.

The average dust temperature, as estimated from Herschel Hi-Gal SED fits (??), is 38 K when including the $70 \mu\text{m}$ data or 26 K when excluding it. This average is obtained over a $\sim 45''$ (~ 1 pc) beam and therefore is likely to be strongly biased toward the hottest dust in the HII regions and around the massive cores, which have temperatures reaching > 300 K (?). Despite these uncertainties, this bulk measurement provides us with a reasonable range to assume for the uncoupled, low-density dust, which (weakly) dominates the mass (see Section 3.8).

One constraint on the dust temperature we can employ is the absolute surface brightness. For some regions, espe-

cially the “filament” and the hot cores noted in Section 2.2, the surface brightness is substantially brighter than is possible for a beam-filling, optically thick blackbody at 20 K, providing a lower limit on the dust temperature ranging from 30 K (40 mJy/beam) to 600 K (1 Jy/beam). Toward most of this emission, optically-thick free-free emission can be strongly ruled out as the driving mechanism using existing data that limits the free-free contribution to be $< 50\%$ if it is optically thick, and negligible ($<< 1\%$) if it is optically thin at radio wavelengths (??).

To gain a more detailed measurement of the dust temperature in regions where it is likely to be coupled to the gas, we use the peak brightness temperature $T_{B,max}$ of lines along the line of sight. If the observed molecule is in local thermal equilibrium, as is expected if the density is high enough to be collisionally coupled to the dust, and it is optically thick, the brightness temperature provides an approximate measurement of the local temperature near the $\tau = 1$ surface. If any of these assumptions do not hold, $T_{B,max}$ will set a lower limit on the true gas temperature. Only nonthermal (maser) emission would push $T_{B,max} > T_{gas}$.

One potential problem with this approach is if the gas becomes optically thick before probing most of the dust. Some transitions, e.g. CO and H_2CO , are likely to be affected by this issue. However, many of the molecules included in the observations have lower abundances and are likely to be optically thin along most of the line of sight.

Some sources have no detected line emission aside from the molecular cloud species CO and H_2CO . The minimum density requirement imposed by a continuum detection at our limit of 1.6 mJy is $n > 10^{7.5} \text{ cm}^{-3}$ for a spherical source. At such high density, it is unlikely that the species are undetected because they are subthermally excited. More likely, the underlying emission source is very compact, optically thick, and/or cold.

Figure 6 shows the distribution of peak line brightnesses for the continuum sources. The spectra used to determine this brightness are the mean spectra over the continuum photometry aperture. To obtain the peak line brightness, we fit Gaussian profiles to each identified line listed in Table ??, rejecting those with poor fits. The line brightnesses reported in the figure are the sum of the continuum-subtracted peak line brightness and the continuum brightness. Excepting CO and H_2CO , which are excluded from the plot, CH_3OH is the brightest line toward most sources.

We use these peak line brightness temperatures to compute the ‘corrected’ masses of the continuum sources. For sources with $T_{B,max} < 20$ K, we assume $T_{dust} = 20$ K to avoid producing unreasonably high masses; in such sources the lines are likely to be optically thin and/or subthermally excited. The correction is illustrated in Figure 7.

3.5.1. W51e2e mass and temperature estimates from continuum

In a $0.21'' \times 0.19''$ beam (1100×1000 au), the peak flux density is 0.38 Jy, which corresponds to a brightness temperature $T_B = 228$ K. This is a lower limit to the surface brightness of the millimeter core, since an optical depth $\tau < 1$ or a filling factor of the emission $ff < 1$ would both imply higher intrinsic temperatures. The implied luminosity, assuming a pure blackbody, is $L = 4\pi r^2 \sigma_{sb} T^4 = 2.4 \times 10^4 L_{\odot}$. Since any systematic uncertainties imply a higher temperature, this estimate is a lower limit on the source luminosity.

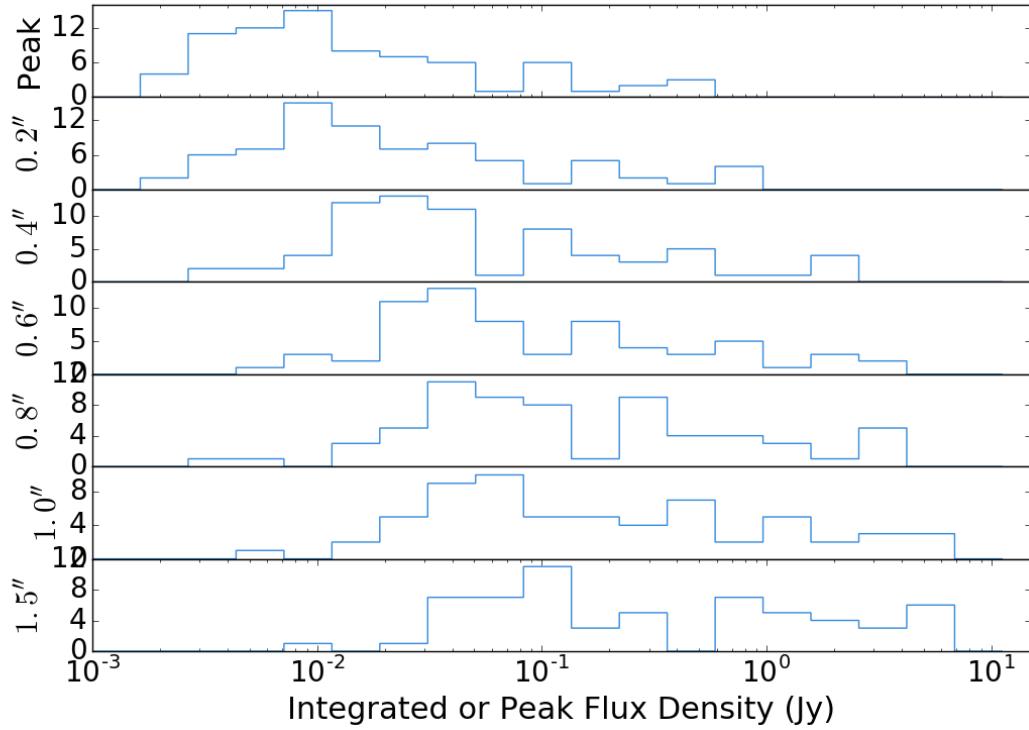


Fig. 4. Histograms of the core flux densities measured with circular apertures centered on the hand-extracted core positions. The aperture size is listed in the y-axis label. For the top plot, labeled ‘Peak’, this is the peak flux density in Jy/beam. For the rest, it is the integrated flux density in the specified aperture.

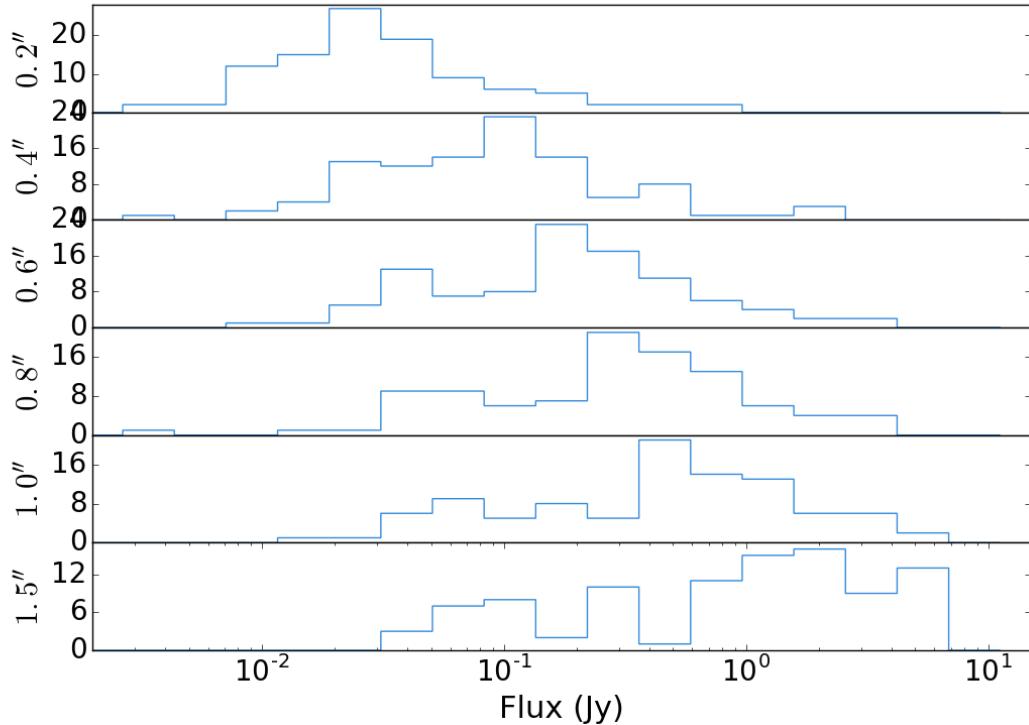


Fig. 5. Histograms of the core flux densities measured with circular apertures centered on the dendrogram-extracted core centroids. The aperture size is listed in the y-axis label. Free-free-dominated sources are excluded.

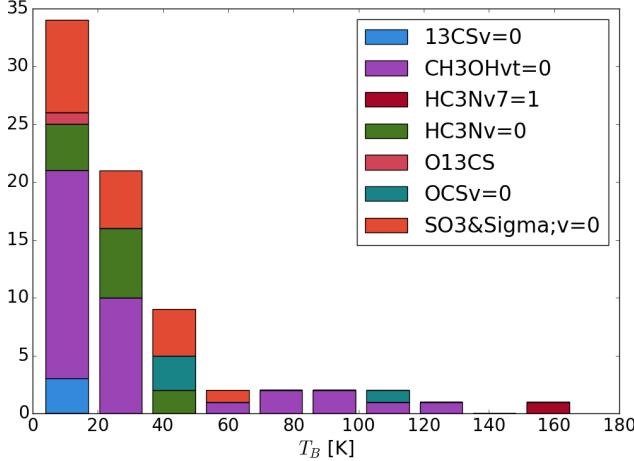


Fig. 6. Histogram of the brightest line toward each continuum source. The bars are colored by the molecular species associated with the brightest line that is not associated with extended molecular cloud emission, i.e., CO and its isotopologues and H₂CO are excluded.

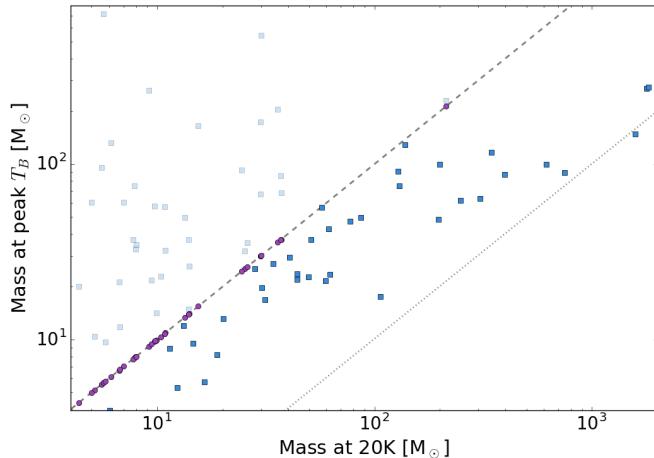


Fig. 7. The mass computed at the peak brightness temperature vs. that computed assuming 20 K for the aperture extracted continuum sources. The faded sources in the top left of the diagram are those with $M(T_{B,\max}) > M(20\text{K})$; the circles along the dashed line show their $M(20\text{K})$. The dashed line shows $M(T_{B,\max}) = M(20\text{K})$ and the dashed line shows $M(T_{B,\max}) = 0.1M(20\text{K})$

If we assume that $T_{dust} = T_{peak}$ and that the dust is optically thin, we derive a dust mass $M_{dust} \sim 20 M_{\odot}$. This mass is not a strict limit in either direction: if the dust is optically thick, there may be substantial hidden or undetected gas, while if the filling factor is low, it may be much hotter and therefore lower in mass. However, simulations and models both predict that the dust will become highly optically thick at radii $r \lesssim 1000$ au (??), so it is likely that this measurement provides only a lower limit on the total gas mass surrounding the protostar.

In the broader region surrounding W51e2e, out to a radius ~ 8000 au, the total mass is $M \approx 1400(T/100\text{K})^{-1} M_{\odot}$ (Figure 8). On these larger scales, a cooler assumed temperature and optically thin dust are more reasonable. The mass heated by e2e is therefore enormous, constituting an entire star cluster's worth of material.

For an independent measurement of the temperature, we use the eight CH₃OH lines in band, ...

How much is the CH₃OH enhanced compared to the surroundings?

3.6. The most massive protostellar cores in W51

In Figure 8, we show the radial profiles extracted from the three high-mass protostellar cores in W51: W51 North, W51 e2e, and W51 e8. The plot shows the enclosed mass out to $\sim 1''$ (5400 AU). On larger spatial scales, the enclosed mass rises more shallowly, indicating the end of the core.

All three sources show similar radial profiles, containing up to $3000 M_{\odot}$ within a very compact radius of 5400 AU (0.03 pc). However, the temperature structure within these sources is certainly not homogeneous, and very likely a large fraction of the total flux comes from $T \gtrsim 300$ K heated material (Section 3.5; ?). If the observed dust were all at 600 K, the mass would be $\sim 17\times$ lower, $100 M_{\odot}$, which we treat as a strict lower bound as it is unlikely that the dust more than $\gtrsim 1000$ au is so warm. Additionally, it is very likely that a substantial mass of cold dust is also present but undetectable because it is hidden by the hotter dust. This paragraph is somewhat redundant with Section 3.5.1, but still useful. Perhaps blend these?

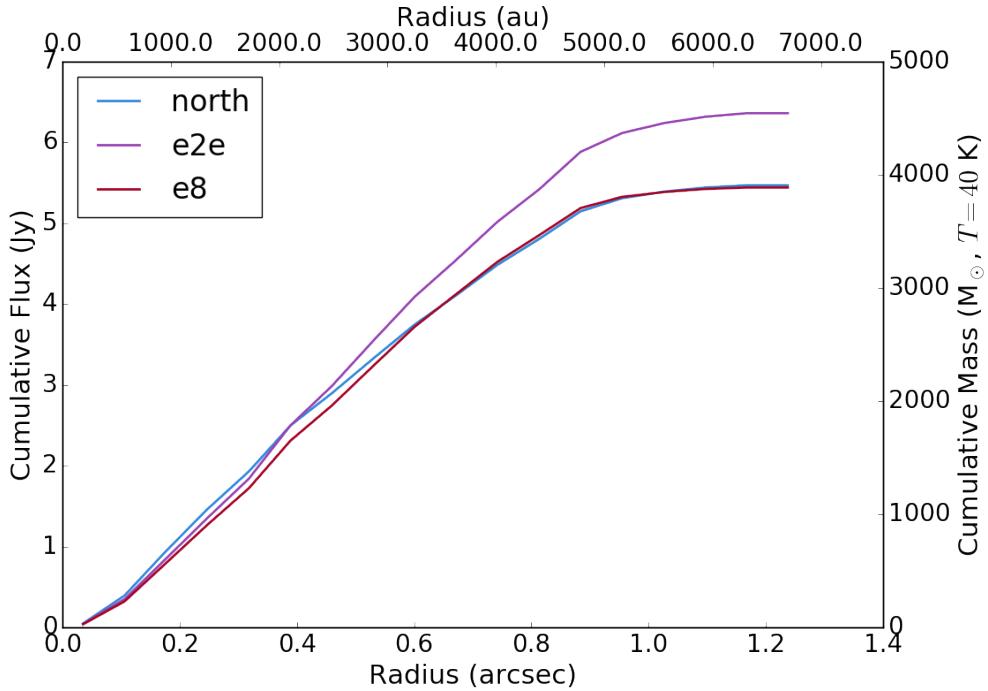


Fig. 8. The cumulative flux density radial profiles centered on three massive protostellar cores. They share similar profiles and are likely dominated by hot dust in their innermost regions, but they are more likely to be dominated by cooler dust in their outer, more massive regions. The cumulative mass distribution may therefore be deceptive.

3.7. The most massive prestellar cores in W51

To place limits on the most massive prestellar cores, we need to know the temperature of the dust in all of the bright (> 15 mJy; $10 M_{\odot}$ at 20 K) sources. We do not have any direct means of evaluating the dust temperature, but we can infer at least a lower limit on it by determining the peak brightness temperature of an optically thick line that is excited at densities $n \gtrsim 10^5 \text{ cm}^{-3}$, at which the dust and gas are coupled.

To accomplish this, we have found the brightest lines across the full ~ 6 GHz spectra and measured their peak brightness temperature.

TODO: use coarser resolution ($2'' = 0.1$ pc?) data to extract “cores” where no smaller (protostellar) cores are detected. Try to estimate their masses. These are the best candidate “prestellar” cores, though likely anything this large is likely to be a massive cluster...

3.8. The mass budget on different spatial scales

An important evolutionary indicator is the amount of mass at a given density; a more evolved (more efficiently star-forming) region will have more mass at high densities. We cannot measure the dense gas fraction directly, but the amount of flux density recovered by an interferometer provides a reasonable approximation.

For the “total” flux density in the region, we use the Bolocam Galactic Plane Survey observations (??), which are the closest in frequency single-dish millimeter data available. We assume a spectral index $\alpha = 3.5$ to convert the BGPS flux density measurements at 271.4 GHz to the mean ALMA frequency of 226.6 GHz. The ALMA data (specifically, the $0.2''$ 12m-only data) have a total flux 23.2 Jy above a very conservative threshold of 10 mJy/beam in

our mosaic; in the same area the BGPS data have a flux of 144 Jy, which scales down to 76.5 Jy. The recovery fraction is $30 \pm 3\%$, where the error bar accounts for a change in $\alpha \pm 0.5$. The threshold of 10 mJy/beam corresponds to a column threshold $N > 1.3 \times 10^{25} \text{ cm}^{-3}$ for 20 K dust. This threshold also corresponds to an optical depth of $\tau \approx 0.5$, implying that a large fraction of the cloud is either approaching optically thick or warmer than 20 K.. For an unresolved spherical source in the $\sim 0.2''$ beam, this column density corresponds to a volume density $n > 10^{8.1} \text{ cm}^{-3}$.

TODO: determine the largest angular scale in the ALMA images. Requires using the simulations.

3.9. Chemically Distinct Regions

3.9.1. Observations

The “hot cores” in W51 (e2, e8, and North) are spatially well-resolved and multi-layered. These cores are detected in lines of many different species spanning areas $\sim 5 \times 10^3 - 10^4$ au across.

Surrounding W51e2e, there are relatively sharp-edged uniform-brightness regions in a few spectral lines over the range $51-60 \text{ km s}^{-1}$ (Figure 11). Some of these features are elongated in the direction of the outflow, but most have significant extent orthogonal to the outflow, spanning $9500 \times 6600 \text{ AU}$. They are prominent in CH_3OH , OCS, and CH_3OCH_3 , weak but present in H_2CO and SO, and absent in HC_3N and HNCO.

Around e8, a similar feature is observed, but in this case CH_3OCH_3 is absent. Toward W51 north, CH_3OH , H_2CO , and SO exhibit the sharp-edged enhancement feature, while the other species do not. The enhancement is from 50-60 km s^{-1} .

By contrast, along the south end of the e8 filament, no such enhanced features are seen; only H₂CO and the lowest transition of CH₃OH are evident.

3.9.2. Interpretation

These enhancements occur as factor of 3-10 increases in the peak brightness of most of the lines shown in Figure 11. These enhancements could occur from increased total column density, increased abundance of the molecules, or increased excitation.

Figure 9 shows a comparison between the CH₃OH 10_{2,9} – 9_{3,6} line and the 225 GHz continuum. While the brightest regions in CH₃OH mostly have corresponding dust emission, the dust morphology traces the CH₃OH morphology very poorly. This difference suggests that the enhanced brightness is not simply because of higher total column density. We examine the dust-CH₃OH link more quantitatively in Figure 10.

The detection of highly excited CH₃OH lines, including 18_{3,15} – 17_{4,14} ($E_U = 447$ K) and 25_{3,22} – 24_{4,20} ($E_U = 802$ K), suggests that the excitation is at least part of the explanation. However, abundance also plays a large role. Figure 10 shows a comparison of the CH₃OH temperature and abundance. The CH₃OH abundance is derived by comparing the rotation-diagram-fitted CH₃OH column density to the dust column density while using the CH₃OH-derived temperature as the assumed dust temperature. The figure shows all pixels within a 3'' (16200 AU) radius of e2e, with pixels having low column density and high temperature (i.e., pixels with bad fits) and those near e2w (which may be heated by a different source) excluded.

The temperature jump at $r \sim 1.5''$ (8100 AU) is substantial, though the floor at greater radii may be artificial... In order to really justify this, I need to flag out the bad fits.

Is the higher abundance hypothesis still supportable given Figure 10? Given the enhanced abundance of CH₃OH in particular, it seems likely that these sharp-edged bubbles represent sublimation zones in which substantial quantities of grain-processed materials are released into the gas phase. The sharp edges likely reflect the particular point where the temperature exceeds the sublimation temperature for each species.

The relative chemical structures of e2, e8, and IRS2 are relatively similar. The same species are detected in all of the central cores. However, in e2, CH₃OCH₃, CH₃OCHO, CH₃CH₂CN, and Acetone ([CH₃]₂ CO) are significantly more extended in e2 than in the other sources. g-CH₃CH₂OH is detected in W51 North, but is weak in e8 and almost absent in e2.

The substructure of different species in e2 is also revealing. Species that are elongated in the NW/SE direction are associated primarily with the outflow (HC₃N, CH₃CH₂CN). Other species are associated primarily with the extended core (CH₃OCHO, CH₃OCH₃, [CH₃]₂ CO). Some are only seen in the compact core (H₂CN, HNCO, NH₂CHO, and vibrationally excited HC₃N). Only CH₃OH and OCS are associated with both the extended core and the outflow, but not the greater extended emission. H₂CCO seems to be associated with only the extended core, but not the compact core. Finally, there are the species that trace the broader ISM in addition to the cores and outflows (H₂CO, ¹³CS, OCS, C¹⁸O and SO). Both HCOOH

and N₂D+ are weak and associated only with the innermost e2e core.

3.10. Temperatures & Columns associated with Chemically Extreme Regions

The extreme chemical regions appear to be associated with regions of dramatically elevated gas temperature. We examine this directly by analyzing the excitation of lines for which we have detected multiple transitions with significant energy differences. We do not use H₂CO for this analysis because it is clearly optically thick (self-absorbed) in the regions of greatest interest.

We produce rotational diagrams for each spatial pixel covering all CH₃OH lines detected at high significance toward at least one position. The detected lines span a range $45 < E_U < 800$ K, allowing robust measurements of the temperature assuming the lines are optically thin, in LTE, and the gas temperature is high enough to excite the lines. These conditions are likely to be satisfied in the e2e, e8, and North cores, except for the optically thin requirement. Luckily, there are some lines in band that have much lower Einstein $A_{i,j}$ values but comparable upper-state energy levels, allowing us to probe higher column densities than would otherwise be possible.

The rotational diagrams are displayed in Figure 16. The line intensities are computed from moment maps integrating over the range (51, 60) km s⁻¹ in continuum-subtracted spectral cubes, where the continuum was estimated as the median over the ranges (25-35, 85-95) km s⁻¹, except for the J=25 lines, which had a continuum estimated from the 10th percentile over the same range to exclude contamination from the SO outflow line wings.

To validate some of the rotational diagram fits, we examined the modeled spectra overlaid on the real. These generally display significant discrepancies, especially at low J where self-absorption is evident. There is clearly a low-temperature component slightly redshifted from the high-J peak that can be seen as a dip within the line profile (Figure 17).

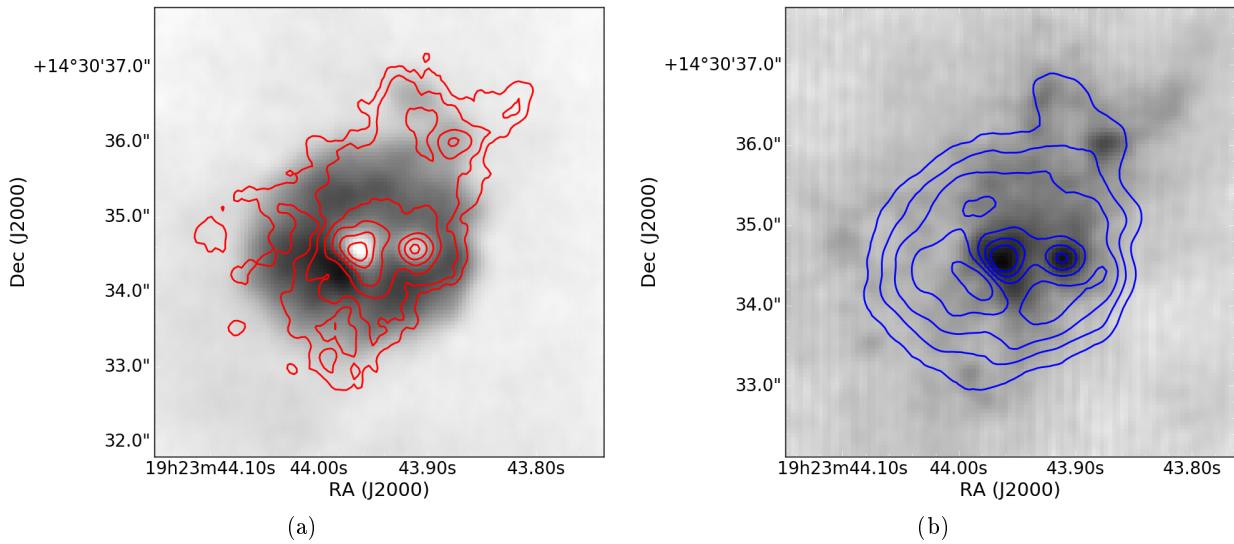


Fig. 9. Images showing CH_3OH $10_{2,9} - 9_{3,6}$ and 225 GHz continuum emission, with CH_3OH in grayscale and continuum in contours (left) and continuum in grayscale, CH_3OH in contours (right). The fainter (whiter) regions in the center of the CH_3OH map correspond to the bright continuum cores and show where all lines appear to be self-absorbed.

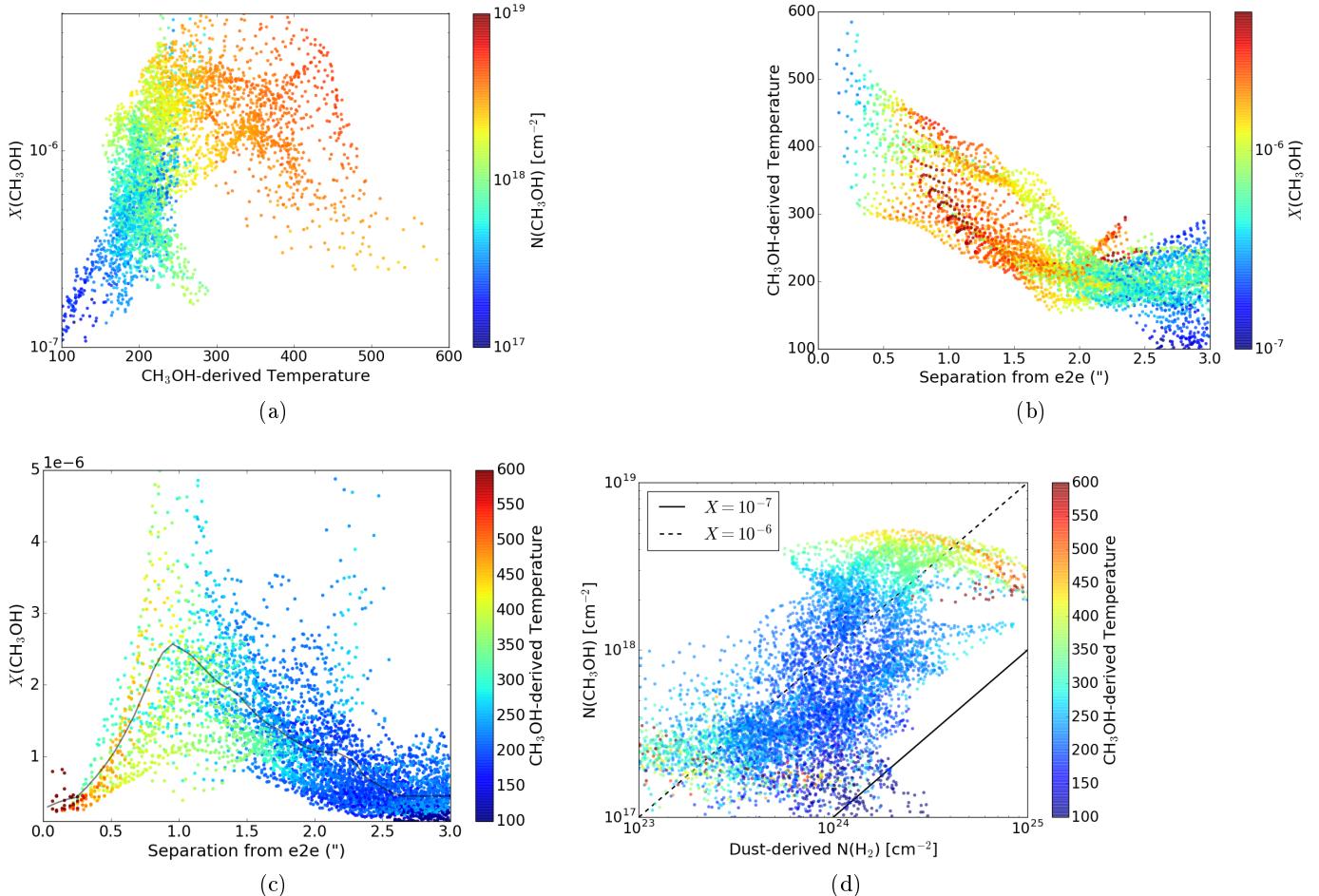


Fig. 10. Comparison of the CH_3OH temperature, column density, and abundance. (a) The relation between temperature and abundance. There is a weak correlation, but most of the high abundance regions are at high temperatures. (b) Temperature vs distance from e2e. There is a clear trend toward higher temperatures closer to the central source (c) Abundance vs distance from e2e. The apparent dip at $r < 1''$ is somewhat artificial, as it is driven by a rising dust emissivity that corresponds to an increasing optical depth in the dust. The CH_3OH column in this inner region is likely to be underestimated. (d) CH_3OH vs dust column density.

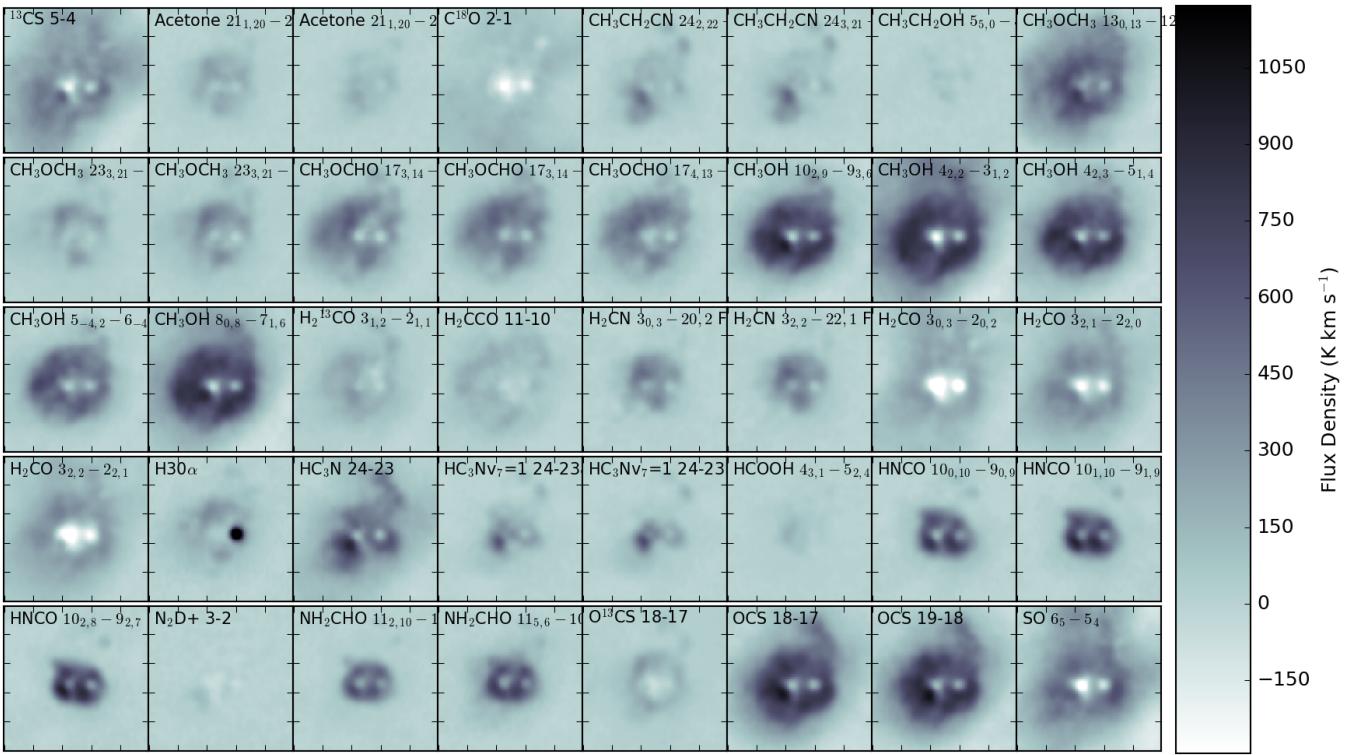


Fig. 11. Moment 0 maps of the e2 region in 40 different lines over the range 51 to 60 km s⁻¹ with continuum subtraction using the 30th percentile emission over the ranges 25-40 and 75-90 km s⁻¹. All images are on the same scale, and the negative features show absorption against the continuum. There is a strong ‘halo’ of emission seen in the CH₃Ox lines and OCS. Extended emission is also clearly seen in SO, ¹³CS, and H₂CO, though these lines more smoothly blend into their surroundings. HNCO and NH₂CHO have smaller but substantial regions of enhancement with a sharp contrast to their surroundings. HC₃N traces the e2 outflow. The bright H30 α emission marks the position of e2w, the hypercompact HII region that dominates the centimeter emission in e2.

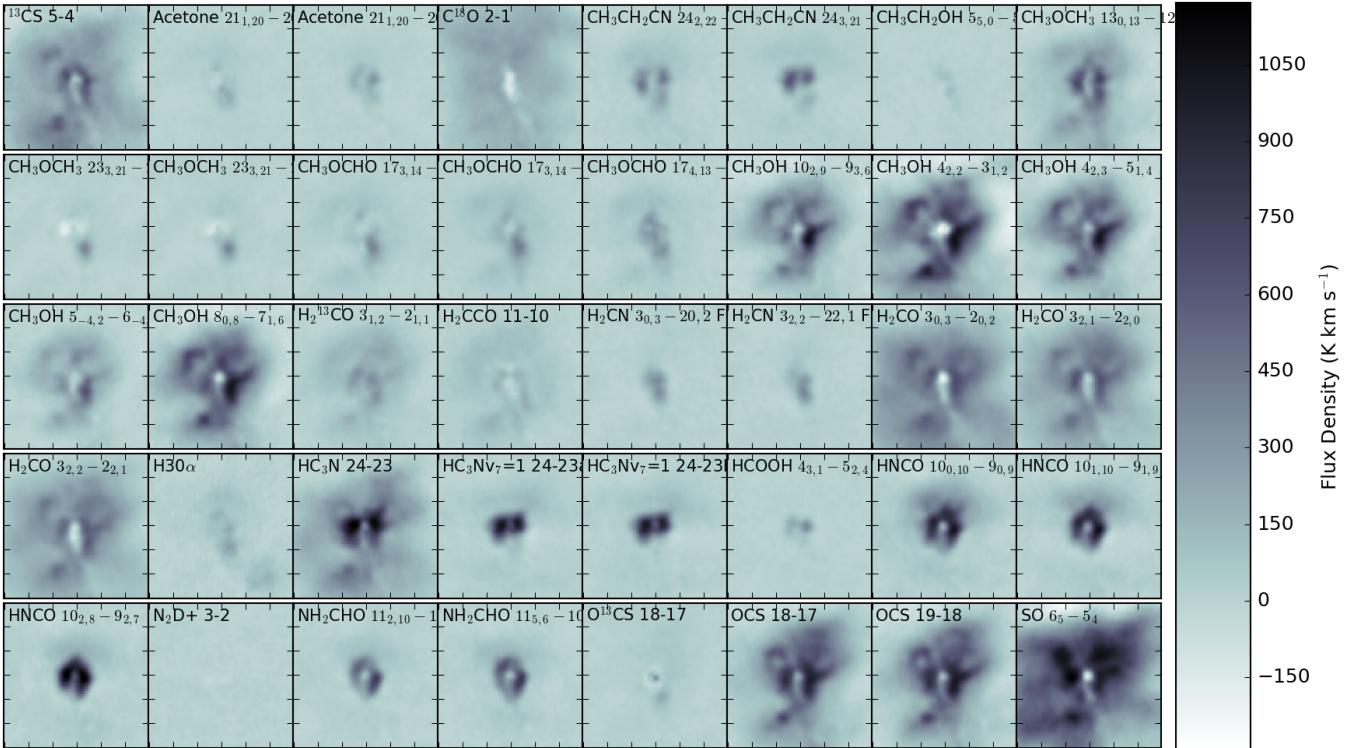


Fig. 12. Moment 0 maps of the e8 region in 40 different lines over the range 52 to 63 km s⁻¹ with continuum subtraction using the 30th percentile emission over the ranges 25-40 and 75-90 km s⁻¹. All images are on the same scale, and the negative features show absorption against the continuum. As in e2, there is extended emission in the CH₃OH and OCS lines, but in contrast, the other CH₃Ox lines are more compact. SO is brighter than OCS in e8, whereas the opposite is true in e2.

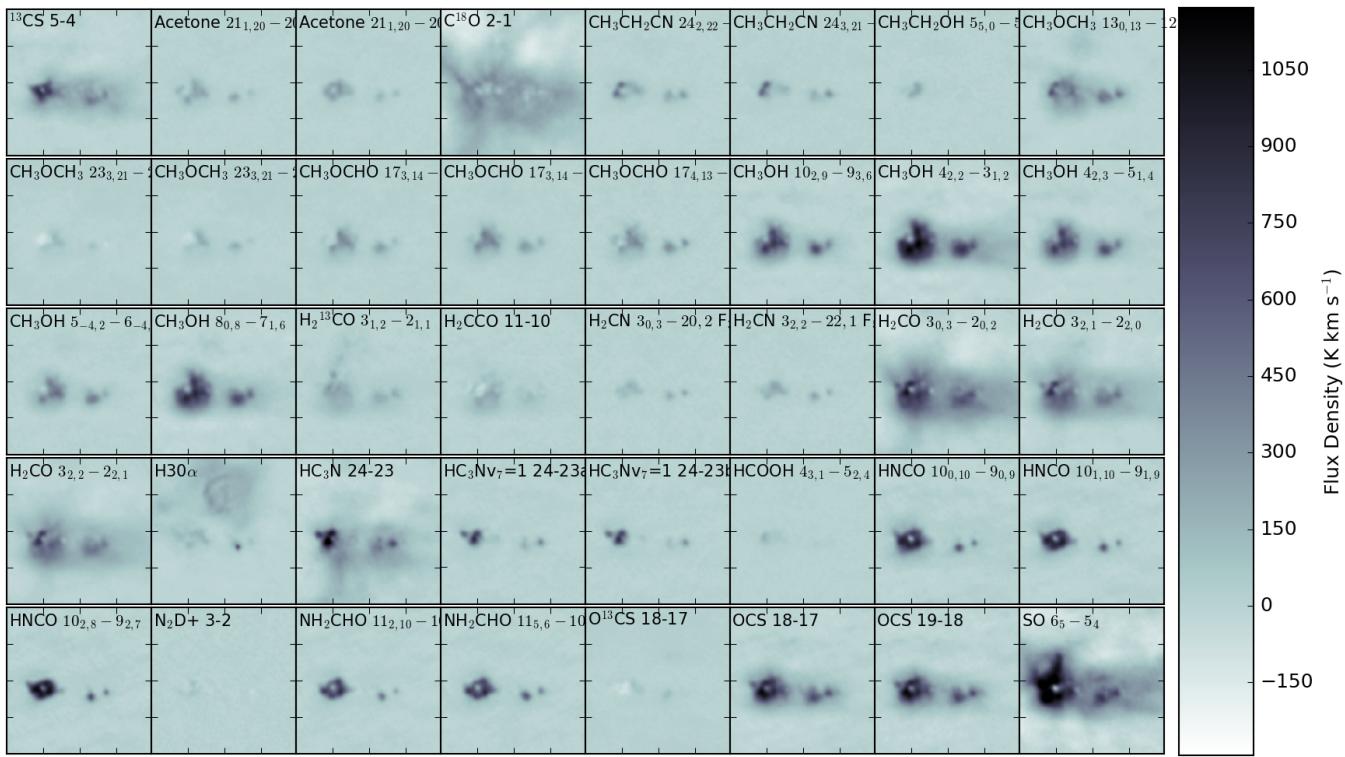


Fig. 13. Moment 0 maps of the W51 IRS2 region in 40 different lines over the range 54 to 64 km s⁻¹ with continuum subtraction using the 30th percentile emission over the ranges 25-40 and 75-90 km s⁻¹. All images are on the same scale, and the negative features show absorption against the continuum. Qualitatively, the relative extents of species seem comparable to e8. The H30_α point source is W51 d2.

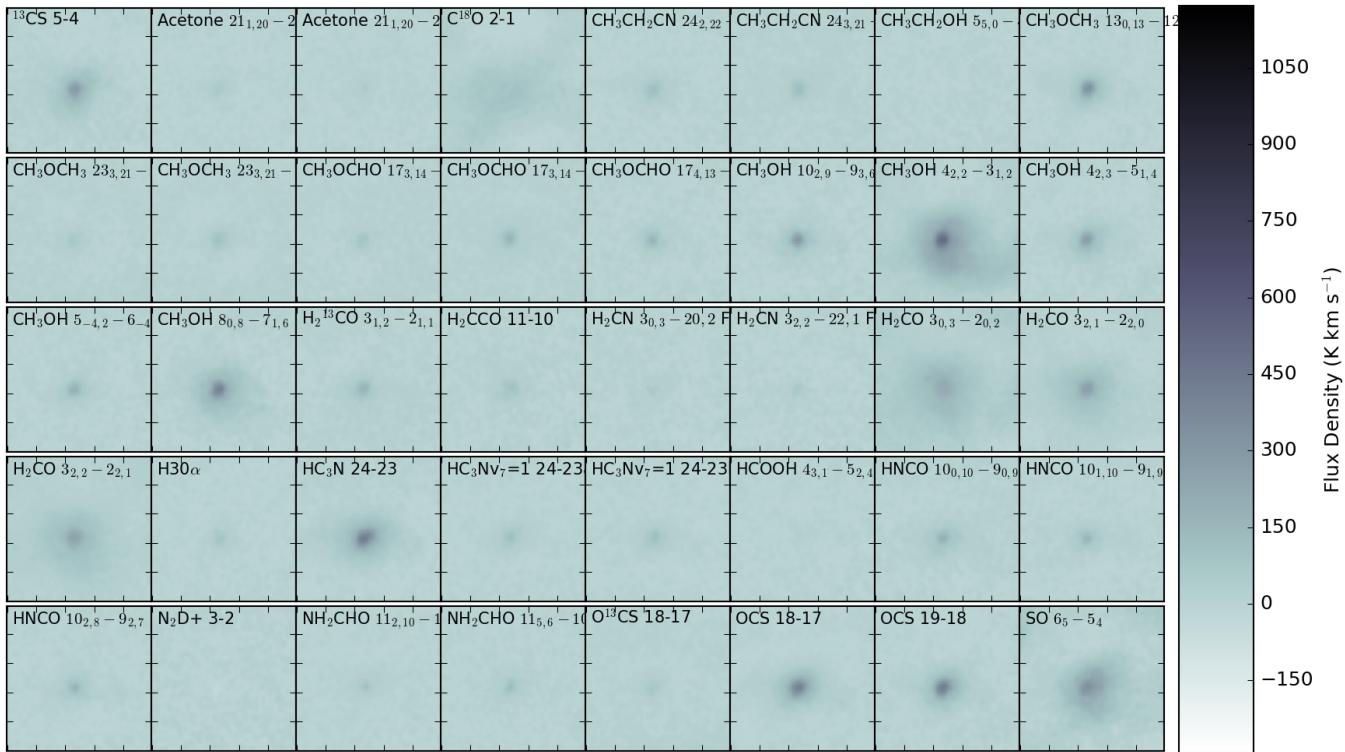
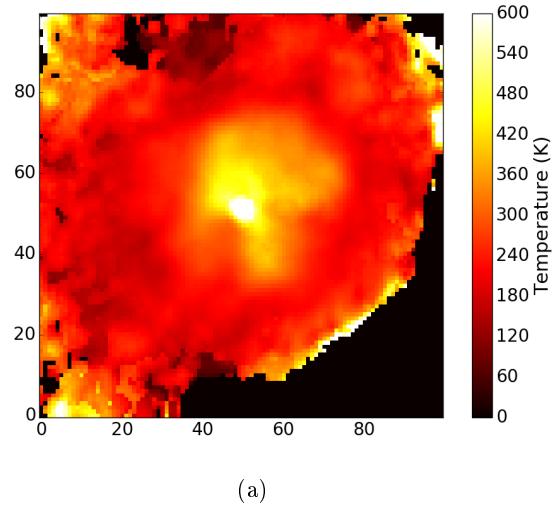
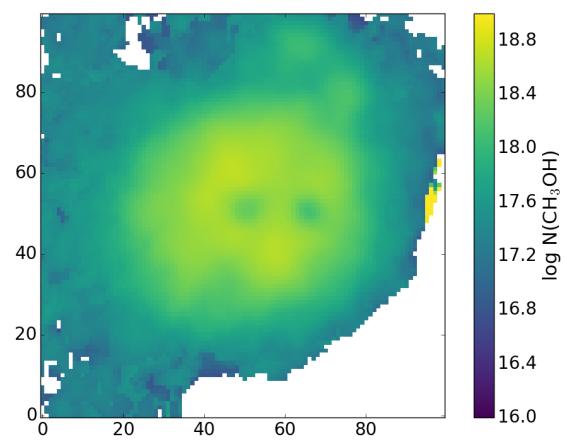


Fig. 14. Moment 0 maps of the ALMAmm14 region in 40 different lines over the range 58 to 67 km s⁻¹ with continuum subtraction using the 30th percentile emission over the ranges 25-40 and 75-90 km s⁻¹. All images are on the same scale. ALMAmm14 is one of the brightest sources outside of e2/e8/IRS2, but it is substantially fainter than those regions. Still, it has a noticeably rich chemistry.



(a)



(b)

Fig. 15. Methanol temperature and column density maps around e2. The temperature goes negative toward the center, where the column densities are highest, strongly indicating that the lines have become optically thick in these regions.

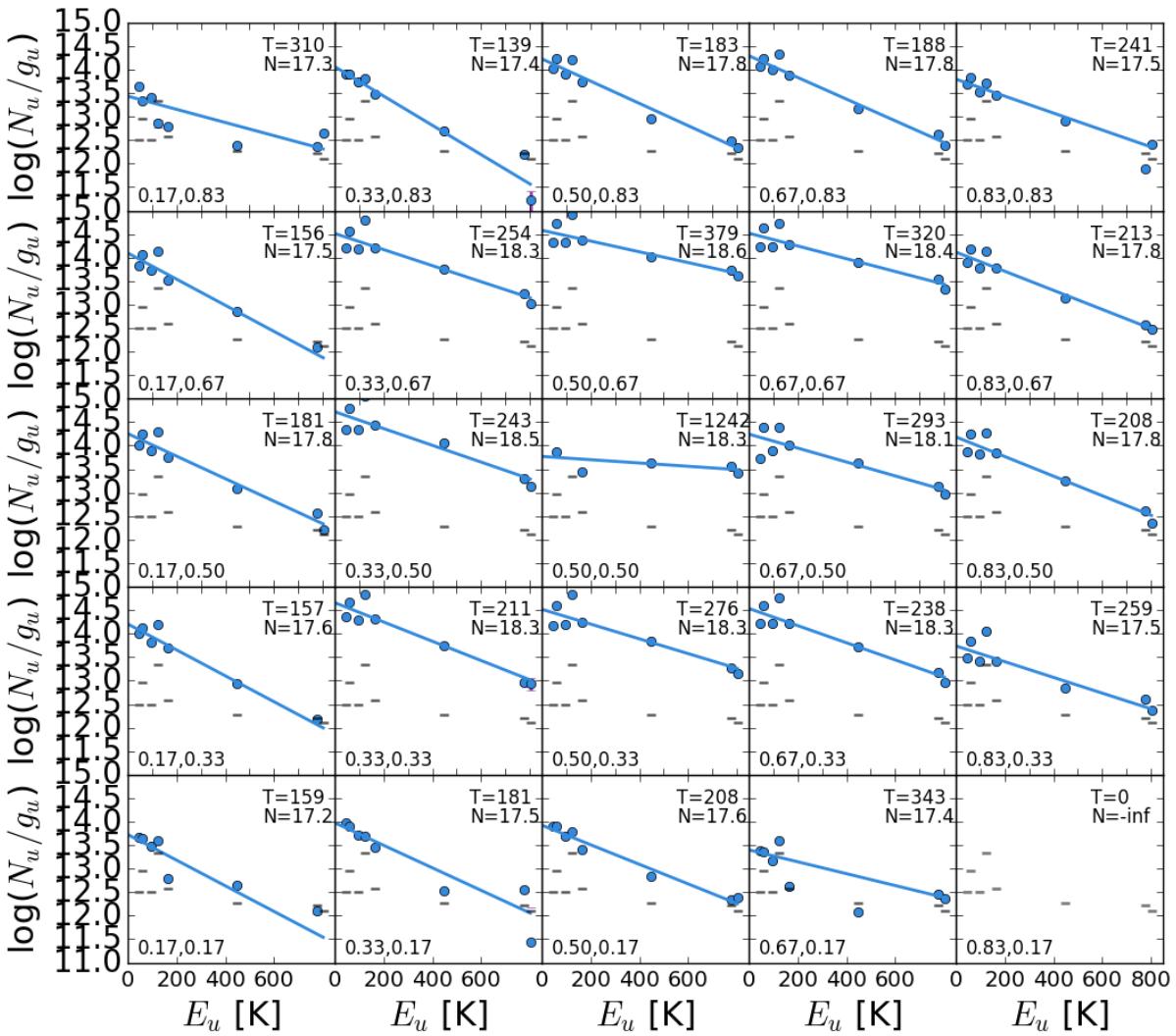


Fig. 16. A sampling of fitted rotation diagrams of the detected CH_3OH transitions. These are meant to provide validation of the temperatures and column densities derived and shown in Figure 15. The lower-left corner shows the position from which the data were extracted in that figure in units of figure fraction. The horizontal black lines show the detection threshold of each of the transitions; points below these lines are ignored when fitting, and instead the threshold itself is used. The fitted temperature and column are shown in the top right of each plot.

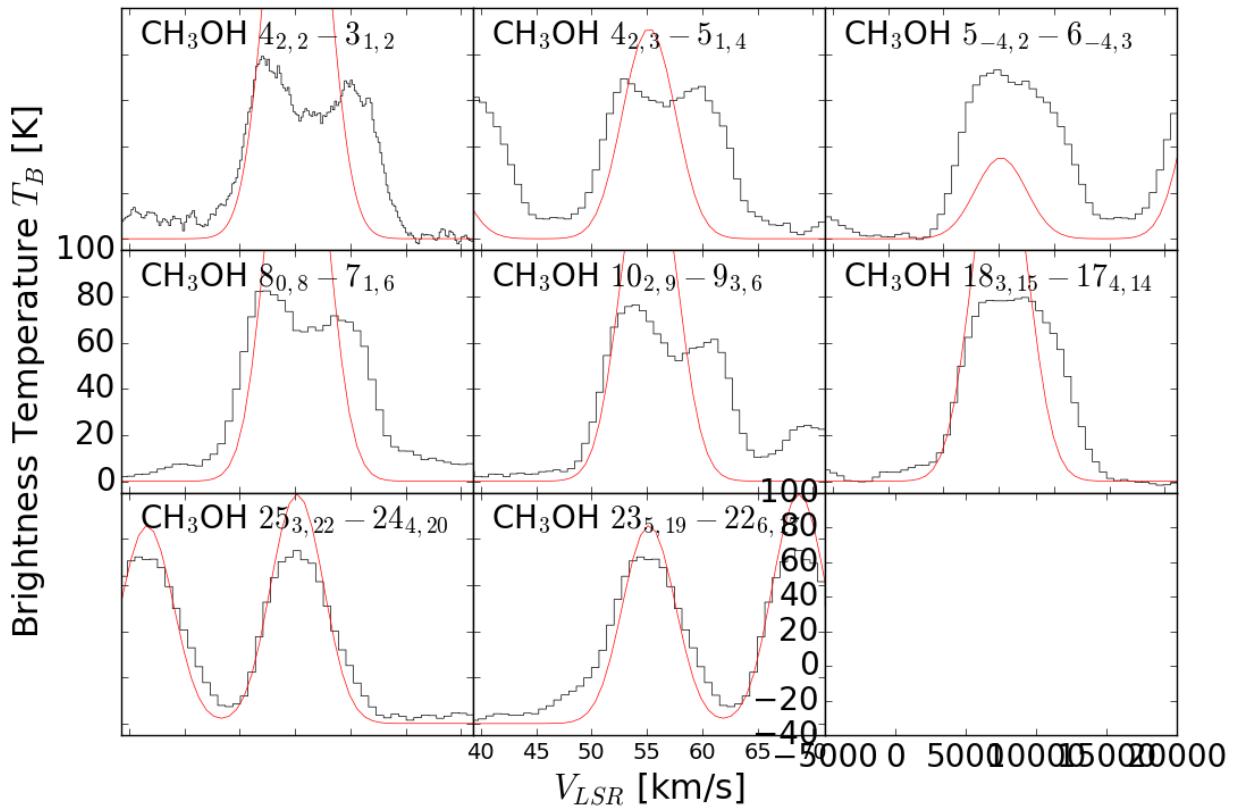


Fig. 17. Spectra of the CH_3OH lines toward a selected pixel just outside of the e2e core. The red curves show the LTE model fitted from a rotational diagram as shown in Figure 16. The model is not a fit to the data shown, but is instead a single-component LTE mode fit to the integrated intensity of the lines shown. As such, the fit is not convincing, and it is evident that a single-temperature, single-velocity model does not explain the observed lines. Nonetheless, a component with the modeled temperature is likely to be present.

3.11. Temperatures derived from H_2CO

The original goal of this project was to measure the gas temperatures in the moderate-density ($n \sim 10^4 - 10^5 \text{ cm}^{-3}$) gas that may correspond to pre-stellar material. We performed the same analysis as was done in ? to create a H_2CO temperature map, but found very high temperatures even in the regions expected to be cold, with a temperature floor around 50 K.

There are a few possible explanations for this high thermal floor. First is purely observational: the maps do not include any zero-spacing information and may therefore have resolved out some emission. It is possible that the $3_{0,3} - 2_{0,2}$ line is preferentially filtered, as it should be the brightest and most widespread of the triplet. This possibility can be examined when zero-spacing data become available.

Second, it is possible that a large fraction of the area of the cloud is optically thick in at least the H_2CO $3_{0,3} - 2_{0,2}$ transition. Such a high optical depth is not expected since the observed brightness temperatures typically peak at ~ 1 K and max out at $\lesssim 15$ K outside of the central protoclusters. Such a low brightness temperature for optically thick gas would imply that the molecules are subthermally excited but highly abundant.

Third, the temperatures could be genuinely high. A Galactic molecular cloud should not be in thermal equilibrium at 50 K, but should readily cool to 10-20 K, so such a cloud would have to be subject to extraordinary heating conditions. Indeed, W51 is subject to some fairly extreme conditions, with one of the Galaxy's most luminous HII regions encompassing most of the molecular material. Even with such heating, though, the densest gas should be able to cool well below 50 K. The UV photons ionizing the HII region cannot penetrate these densest regions and the infrared radiation field is not strong enough to maintain such a high floor (is it?). Curiously, the CO 3-2 maps of ? exhibit peak brightness temperatures up to 50 K within the mapped region, so it is plausible that the moderate-density medium is much warmer than in a typical cloud.

To evaluate this third option, current data are insufficient. Ruling out option (1), filtering, would be help-

ful but not definitive. Additional observations of $J=2$ and $J=4$ H_2CO transitions or the $H_2^{13}CO$ $J=3$ lines would be enough to rule out hypotheses (1) and (2).

4. Outflows

We detected many outflows, primarily in CO 2-1 and SO $6_5 - 5_4$. The flows are weakly detected in some other lines, e.g. H_2CO , but we defer discussion of outflow chemistry to....

In this section, we discuss some of the unique outflows and unique features of outflows in the W51 region.

4.1. The Lacy jet

A high-velocity outflow was discovered within the W51 IRS2 region by ?, and subsequently detected in $H77\alpha$ by ?. We have now discovered the CO counterpart to this outflow, which comes from source XXX. The outflow shows red- and blue-shifted flows that form the base of the ionized outflow reported by ?.

Additionally, we have reduced archival VLT SINFONI observations of the region and discovered a 2-micron H_2 knot positioned directly between the cold molecular (CO) and the ionized components of the flow. This H_2 emission reveals the position at which the CO is breaking out of the cloud and into the H II region.

4.2. The e2e outflow

The dominant outflow in W51, which was previously detected by the SMA (), comes from the source e2e. This outflow is remarkable for its high velocity, extending nearly to the limit of our spectral coverage. The ends of the flow cover at least $-50 < v_{lsr} < 160 \text{ km s}^{-1}$, or a velocity $v \pm 100 \text{ km s}^{-1}$.

The morphology is also notable. Both ends of the outflow are sharply truncated at $\sim 2.5''$ (0.07 pc) from e2e. To the southeast, the high-velocity flow lies along a line that is consistent with the extrapolation from the northwest flow, but at lower velocities ($10 < v_{LSR} < 45 \text{ km s}^{-1}$), it jogs toward a more north-south direction. In the northwest, the redshifted part of this flow ($70 < v_{LSR} < 120 \text{ km s}^{-1}$) apparently collides with a blueshifted flow from another source ($22 < v_{LSR} < 45 \text{ km s}^{-1}$), suggesting that these outflows intersect, though such a scenario seems probabilistically implausible given their small volume filling factor.

The extreme velocity and morphology carry a few important implications for the accretion process in W51. The sharp symmetric truncation, combined with the extraordinary velocity, suggests that the outflow is freshly carving a cavity in the surrounding dense gas. The observed velocities are high enough that their bow shocks likely dissociated all molecules, so some ionized gas is likely present at the endpoints; this ionized gas has not been detected in radio images because of the nearby 100 mJy HCHII region e2w. The dynamical age of the outflow is ~ 600 years at the peak observed velocity, which is a lower limit on the true age of the outflow.

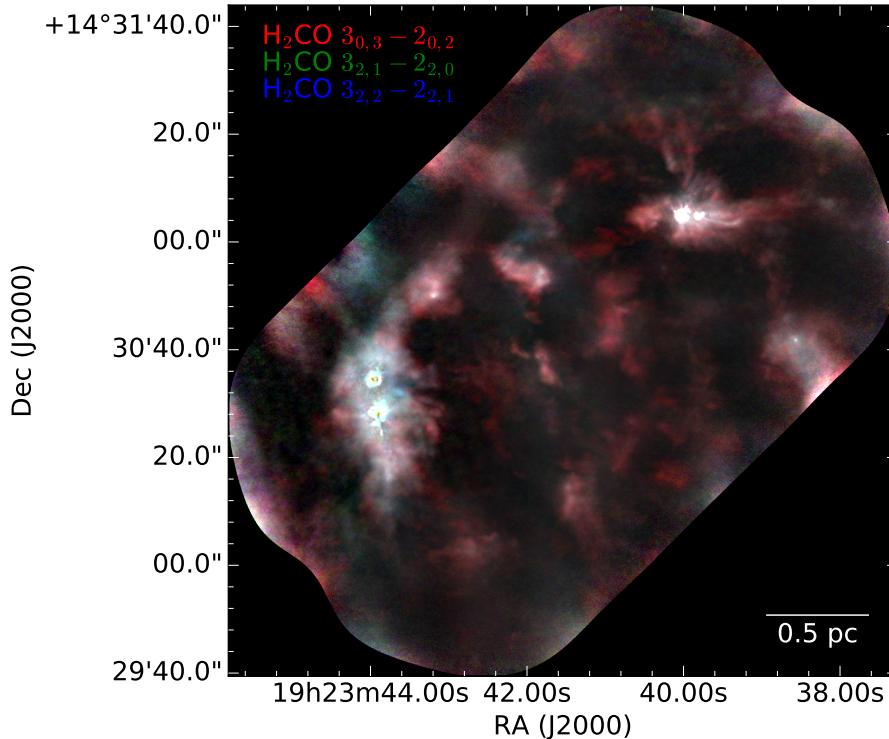


Fig. 18. An RGB composite image of the peak intensity of the three H₂CO lines. The red channel, 3_{0,3} – 2_{0,2}, has an upper-state energy level 23 K, so redder regions are qualitatively cooler than whiter or bluer regions. However, the solid white zones around W51 e2, e8, and north are areas where all three lines become very optically thick, so the color no longer implies anything about the temperature.

4.3. e8

There are at least four distinct outflows coming from the e8 filament. The e8 core is launching a redshifted outflow to the northwest. A blueshifted outflow is coming from somewhere south of the e8 peak and pointing straight east. While these originate quite near each other, they seem not to have a common source, since the red and blue streams are not parallel.

4.4. north

The outflow from W51 north is extended and complex.

A jet-like high-velocity feature appears directly to the north of W51 north in both CO and SO. However, in SO, this feature begins to emit at $\sim 47 \text{ km s}^{-1}$ and continues to $\sim 100 \text{ km s}^{-1}$. The CO emission below $< 70 \text{ km s}^{-1}$ is completely absent, presumably obscured by foreground material. The blueshifted component, by contrast with the red, points to the southeast and is barely detected in CO, but again cleanly in SO. It is sharply truncated, extending only $\sim 1''$ ($\sim 5000 \text{ AU}$). Unlike the Lacy jet, there is no evidence that this outflow transitions into an externally ionized state.

The northernmost point of the W51 North outflow may coincide with the ? H₂ and [Fe II] outflow. There is some CO 2-1 emission coincident with the southernmost point of the H₂ features, and these all lay approximately along the W51 North outflow vector. However, the association is only circumstantial.

5. Feedback in W51

5.1. Ionizing Radiation

This was covered in (?). Ionizing radiation affects much of the cloud, but little of the prestellar material. There is no evidence of increased gas temperatures in the vicinity of H II regions. While in Section 5.3 we identify chemically enhanced regions as those where radiative feedback has heated the dust and released ices into the gas phase, no such regions are observed surrounding the most luminous compact H II regions.

What direct tests can be used to show that H II regions aren't heating their surroundings? H₂CO is good, in principle, but maybe not in practice because of the possible optical depth issues. Radio NH₃ might be OK, but it might also be affected by imaging artifacts from the bright radio sources.

5.2. Outflows

While the outflows described in Section 4 are impressive and plentiful, they are obviously not the dominant form of feedback, as their area filling factor is small compared to that of the various forms of radiative feedback. A low area filling factor implies a substantially smaller volume filling factor and therefore a lower overall effect on the cloud. However, these outflows likely do punch holes through protostellar envelopes and the surrounding cloud material, allowing radiation to escape.

The detection of widespread high-J CH₃OH emission around the highest-mass protostars suggests that the use of CH₃OH as a bulk outflow tracer as suggested by ? is

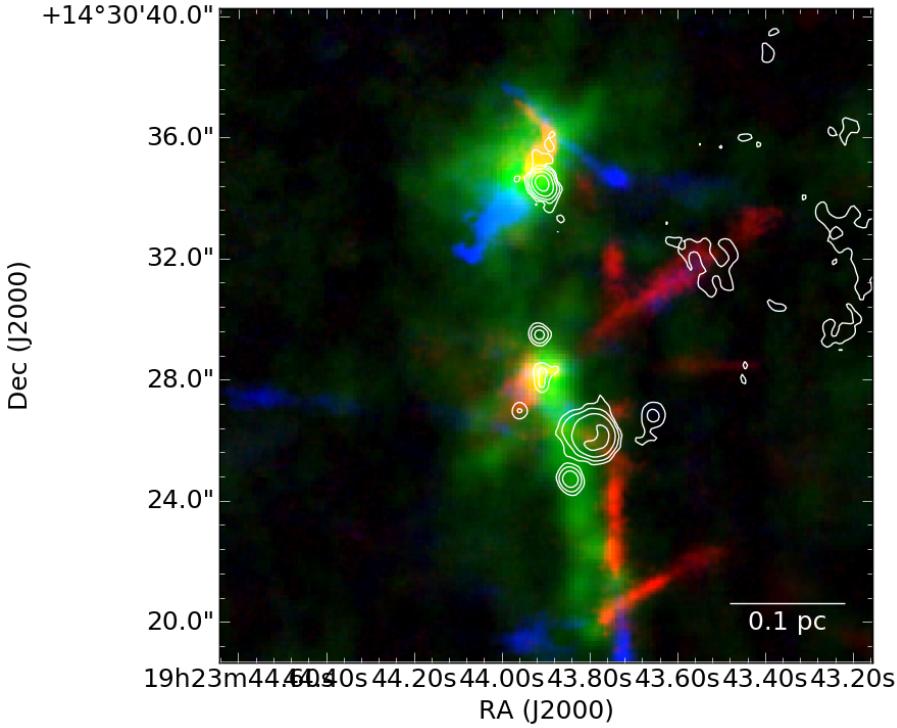


Fig. 19. Outflows in red and blue overlaid on mm continuum in green with cm continuum contours in white.

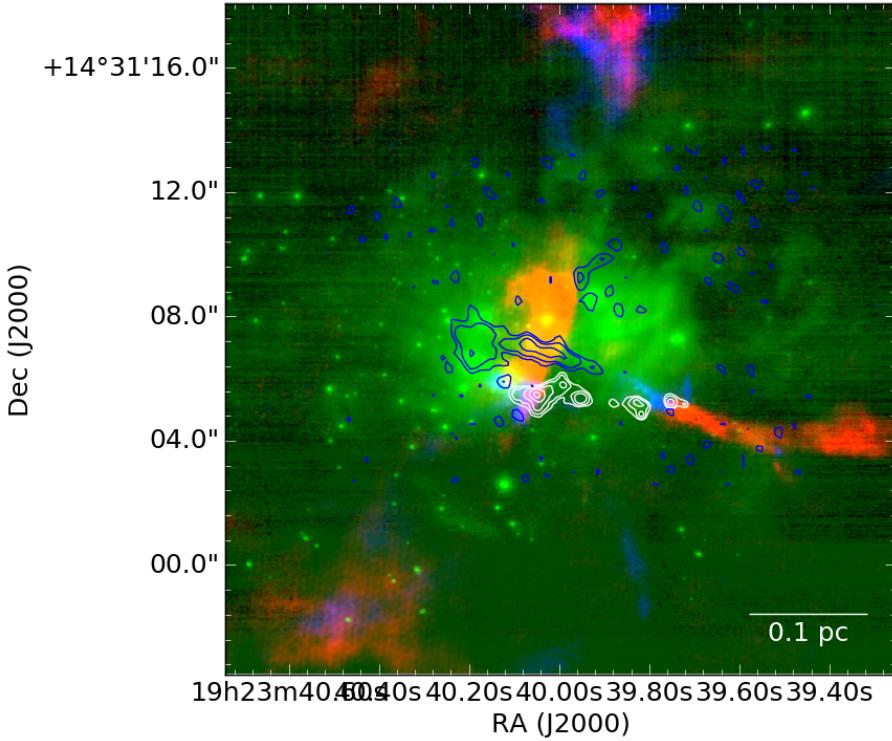


Fig. 20. Outflows in the W51 IRS2 region. The green emission is NACO K-band continuum, with ALMA 1.4 mm continuum contours in white and H77 α contours in blue. The ? jet is prominent in H77 α .

not viable. While mid-J CH₃OH emission is detected associated with the outflow (e.g., the J=10-9 transition), it is completely dominated by the general ‘extended hot core’ emission described in Section 3.9.

5.3. Non-ionizing Radiation

The formed and forming protostars are producing a total $\gtrsim 10^7 L_\odot$ of far infrared illumination (?). This radiation heats the cloud’s molecular gas, affecting the initial conditions of future star formation.

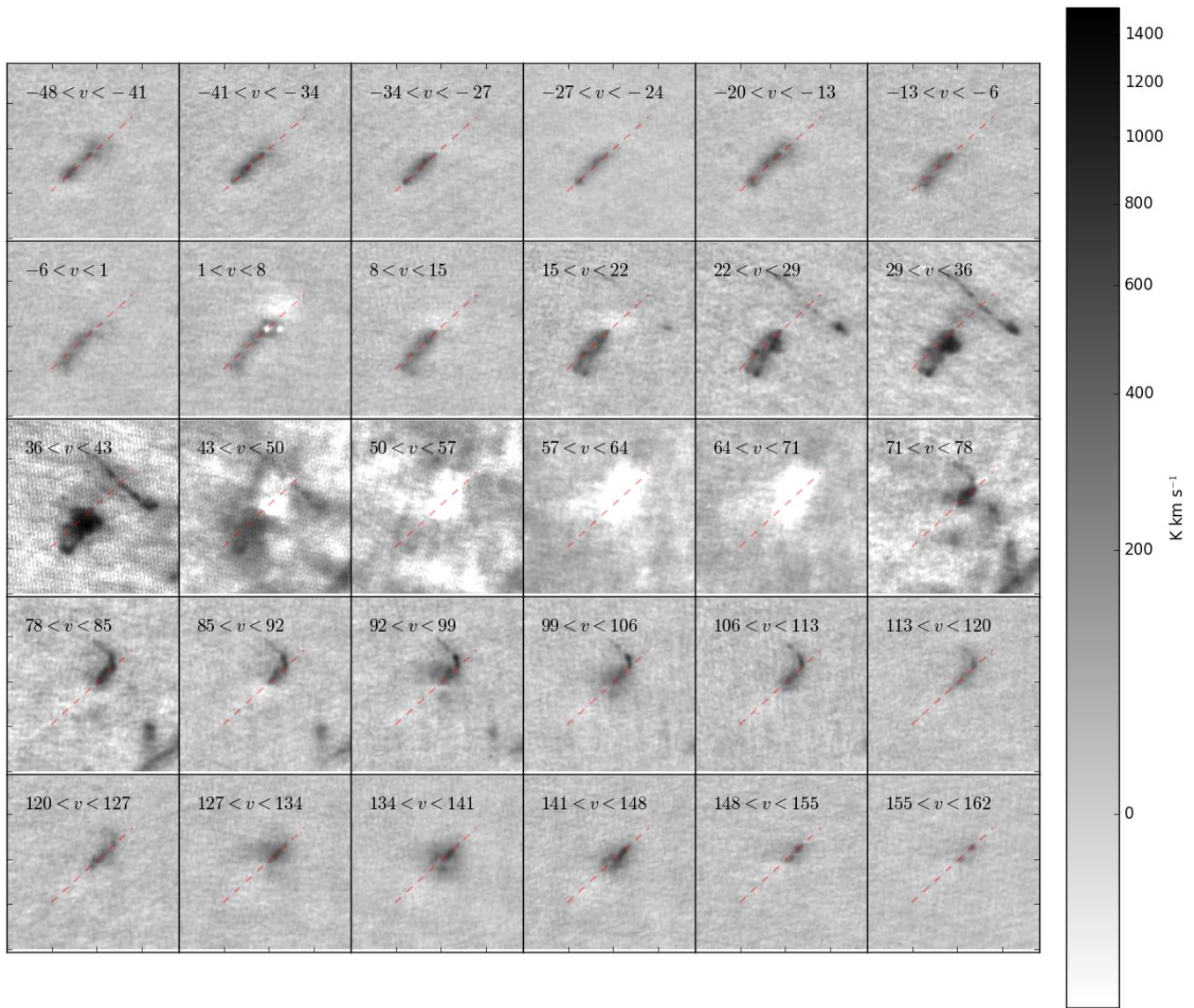


Fig. 21. Channel maps of the e2e outflow in CO 2-1. The dashed line approximately connects the northwest and southeast extrema of the flow.

The chemical maps shown in Section 3.9 show the volumes of gas clearly affected by newly-forming high-luminosity stars. The CH₃OH-enhanced region around W51e2 extends 0.04 pc, or 8500 AU. Other locally enhanced species, especially the nitrogenic molecules HNCO and NH₂CHO, occupy a smaller and more asymmetric region around e2e and e2w (Figure 24).

The extraordinarily high column densities of CH₃OH make direct temperature estimation impossible; many or all of the observed CH₃OH lines are almost certainly optically thick. Fitted rotational diagrams resulted in negative temperatures throughout the CH₃OH-enhanced region, implying that the levels are not thermally populated. However, the total column densities from these rotational diagram fits are reasonable lower-limits on the column, and they exceed $N(\text{CH}_3\text{OH}) \gtrsim 10^{20} \text{ cm}^{-2}$. (demonstrate this?)

If we assume $T_{\text{ex}} = 100 \text{ K}$, can we use the 5_{-4,2} – 6_{-4,3} line to measure the column density? Out of the five clearly detected CH₃OH lines, the 5_{-4,2} – 6_{-4,3} line

How does the CH₃OH brightness/column profile compare with the dust brightness/column? Is it going up faster? By how much?

Is there any evidence that the main-sequence stars that illuminate the H II regions in W51 (?) affect the pre-star-forming gas throughout W51? Our ALMA program was designed to answer this question by measuring the temperature in the dense prestellar H₂CO-rich gas. Naively, the data say "yes, the temperatures are all ridiculously high, $T > 100 \text{ K}$ ", but that can't be. The H₂CO temperatures suggest that temperature is correlated with density, which unfortunately suggests instead that the H₂CO line optical depth is correlated with density. It is therefore not straightforward to systematically examine the thermal feedback effects from MYSOs.

Notes from chatting with Wing-Fai Thi: CH₃OH has a similar condensation temperature to water, so the desorbed region is probably $\sim 90 - 100 \text{ K}$. HNCO has a much lower desorption temperature, so if it was coming from grain surfaces, it should be more widespread than CH₃OH. Since

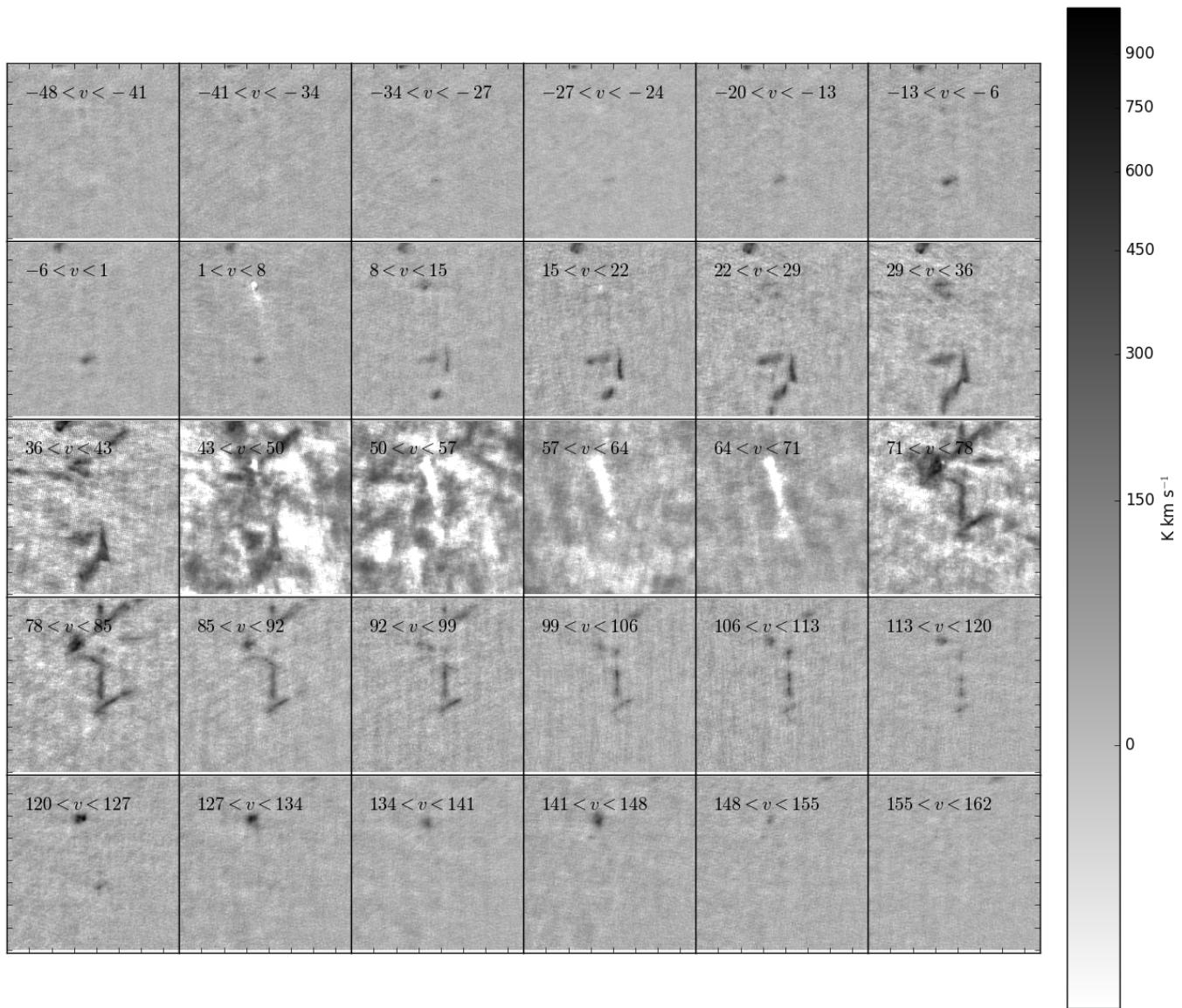


Fig. 22. channel maps of the e8 outflow in CO

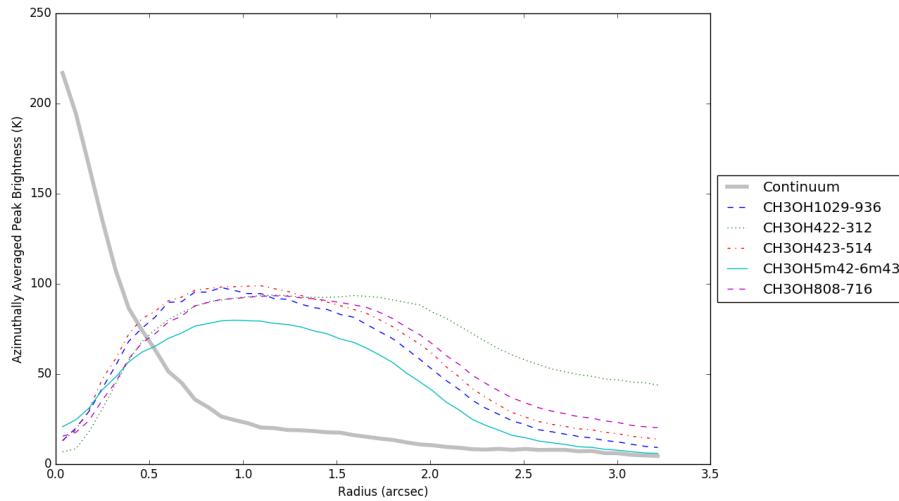


Fig. 23. Radial profiles of the peak surface brightness of five CH₃OH transitions along with the profile of the continuum brightness. The radial profiles were constructed from images with 0.2'' resolution including only 12m data. The central dip shows where the lines go into absorption, though they are only seen in absorption at $\sim 55 \text{ km s}^{-1}$. The CH₃OH lines are continuum-subtracted.

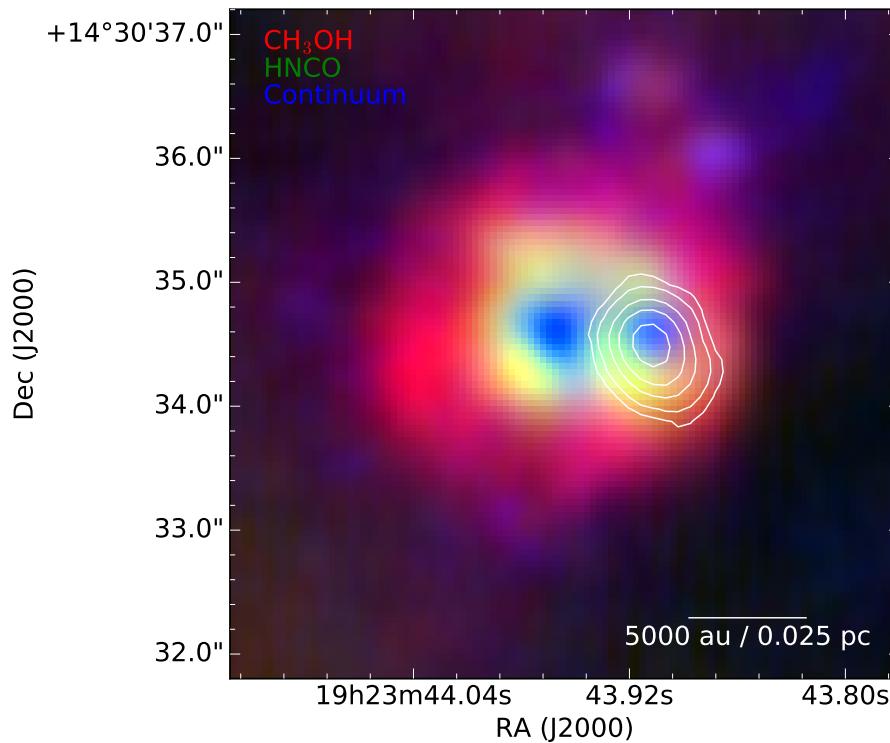


Fig. 24. Image of CH_3OH 8_{0,8} – 7_{1,6} (red), HCNO 10–... (green), and 225 GHz continuum (blue) toward W51 e2e. The contours show Ku-band radio continuum emission tracing the H II region W51 e2w. The CH_3OH emission is symmetric around the high-mass protostar W51 e2e, suggesting that this forming star is responsible for heating its surroundings.

it is not, the enhancement is most likely due to gas-phase chemistry.

However, Ewine van Dishoeck pointed out that HCNO and NH_2CHO can be mixed into ices that evaporate at a much higher temperature, consistent with the structure we observe.

6. Discussion

6.1. The nature of the continuum sources

We have detected up to 113 distinct compact ‘sources’ and characterized some of their basic properties assuming they consist purely of gas and dust, but this interpretation is incomplete. At the least, all of the sources with peak surface brightnesses $T_{B,\max} > 30$ K are likely to contain central heating sources, i.e., stars or protostars.

We fit each of up to ~ 50 lines (see Table ...) with Gaussian profiles to attempt to determine the line width of each source. Most sources were detected in at least ~ 5 –10 lines, though some of these are associated with interstellar rather than circumstellar material, i.e., H_2CO , CO, ^{13}CS , HC_3N . In all cases where unambiguous Gaussian fits were acquired, the line widths are not consistent between different tracers.

demonstrate this Generally, the obviously interstellar features are narrower.

idea: concentration parameter, compare to power-law cores of varying indices. Protostar / core ratio on this basis? Evolutionary indicator of subregions?

6.2. Limits on accretion onto HII regions

? and ? proposed that ultra- and hyper-compact H II regions may be variably accreting. When accretion is most active, the H II region is confined and shrinks or may even be turned off. When accretion is slower or weaker, the H II region expands, following approximately Strömgren expansion make sure that’s actually what they say....

The observed lack of warm molecular gas around compact H II regions suggests that they have not recently been accreting...

d2 provides a counterpoint, however, as it is a hyper-compact H II region that *does* exhibit enhanced molecular emission in its surroundings

6.3. Question: Where does the radiation from the HII regions end up?

The H II regions show no signs of heating around them. However, we know that these must be $> 10^4 L_\odot$ stars, and even the infrared radiation should be rising with luminosity (or temperature). While most of the energy might go into ionizing the gas cloud, many of the photons must get reprocessed into the infrared at some point. If optical/NIR photons were escaping, we should be able to see them unless the geometry is particularly unfavorable.

idea: dust is more concentrated than gas (compare PSDs). Can we do this to sims and determine which lines are thick?