

HOT CORE, OUTFLOWS AND MAGNETIC FIELDS IN W43-MM1 (G30.79 FIR 10)

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ABSTRACT

We present submillimeter spectral line and dust continuum polarization observations of a remarkable hot core and multiple outflows in the high-mass star-forming region W43-MM1 (G30.79 FIR 10), obtained using the Submillimeter Array (SMA). A temperature of ~ 400 K is estimated for the hot-core using CH₃CN (J=19-18) lines, with detections of 11 K-ladder components. The high temperature and the mass estimates for the outflows indicate high-mass star-formation. The continuum polarization pattern shows an ordered distribution, and its orientation over the main outflow appears aligned to the outflow. The derived magnetic field indicates slightly super-critical conditions. While the magnetic and outflow energies are comparable, the B-field orientation appears to have changed from parsec scales to ~ 0.1 pc scales during the core/star-formation process.

Subject headings: stars: formation - stars: formation

1. INTRODUCTION

The process of high-mass star-formation and early evolution is marked by the phenomena of outflows (for example Shepherd & Churchwell, 1996; Beuther et al. 2002; Zhang et al. 2005) and hot cores (e.g. Cesaroni, Walmsley & Churchwell, 1992; Cesaroni et al. 2010). Precious little is known about the role of magnetic fields in the process (e.g. DR21(OH), Lai et al 2003; Girart et al. 2013; G34.41 Cortes et al., 2008; G31.41, Girart et al., 2009; IRAS18089-1732, Beuther et al, 2010; W51, G5.89, Tang et al., 2009a,b,2013). Due to the large distances to high-mass star-forming regions, interferometric studies are critical to gain better understanding, as in the above examples. It is also necessary to study regions in early stages of evolution, preferably the high-mass proto-stellar object phase (HMPOs, e.g. Sridharan et al 2012) or younger, to probe pristine conditions. In this Letter, we report the discovery of a high temperature hot-core and multiple outflows towards such an early stage object, W43-MM1 (G30.79 FIR10), and the magnetic field distribution around it, using submillimeter wavelength spectral line and continuum polarization observations at 345 GHz, obtained with the Submillimeter Array¹⁰(SMA; Ho, Moran & Lo, 2004).

2. OBJECT AND OBSERVATIONS

W43-MM1, also known as G30.79 FIR 10, is the brightest dust emission core in the W43 "mini-starburst" region (Motte, Schilke & Liz, 2003; Bally et al 2010). The region harbours UC-HII regions and water and methanol masers marking high-mass star-formation. The FIR10/MM1 core

is at the head of a cometary infra-red dark cloud located at 5.5 kpc (from maser parallax; Zhang et al, 2013), facing a giant HII region powered by a cluster of WR-OB stars. It is devoid of cm-wavelength emission which may suggest an early, HMPO evolutionary stage. In addition, evidence for infall in multiple spectral lines, accretion at high rates and extended SiO emission possibly due to colliding flows have also reported (Cortes et al., 2010; Cortes, 2011; Herpin et al., 2012; Nguyen-Luong et al, 2013), making the region very interesting. Polarized dust emission at 1.3mm suggested an inconclusive pinched morphology for the magnetic field (Cortes & Crutcher, 2006), with a field strength of 1.7 mG, implying a near critical mass-to-magnetic flux ratio of 0.9, later refined to 1.9 (Cortes, 2011). If magnetic support was dominant in the natal core, a pinched morphology is expected.

The SMA observations reported here, intended to delineate the B-field better, and to study line emission from the core, were obtained in the sub-compact and compact configurations. The observations were conducted on 24 April, 2007 and 28 May, 2008 under excellent weather conditions with a 225 GHz zenith opacity of ~ 0.05 . The sub-compact observations only had 5 antennas. The receivers were tuned to 346.51 & 349.42 GHz at the center of the upper side-band for the two observations with the phase center at $(\alpha, \delta) = 18:47:47.0, -01:54:30.0$ (J2000). The correlator was configured to provide a uniform resolution of 0.81 MHz (0.7 kms^{-1} at 349 GHz). The combined data have a UV coverage of 16-160 $k\lambda$. The polarization, phase and flux calibrators were 3c273, 1791-09 and Uranus re-

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¹⁰ The Submillimeter Array is a joint project between the Smithsonian Astrophysical Observatory and the Academia Sinica Institute of Astronomy and Astrophysics, and is funded by the Smithsonian Institution and the Academia Sinica.

spectively. Standard data reduction procedures were used under MIRIAD. A discussion of the SMA polarimetry system can be found in Marrone et al. (2006) and Marrone & Rao (2008). For continuum, multi-frequency synthesis was used to combine the two data sets with slightly differing frequencies, by 3 GHz, for the two tracks.

3. CONTINUUM EMISSION AND MAGNETIC FIELD

The continuum emission, mapped using the combined data from the two configurations at a beam size of $2.5'' \times 2.1''$, shows multiple peaks (fig. 1) with integrated fluxes and masses in the range 1–10 Jy and 100–1000 M_{\odot} (Table 1). All the parameters of the cores were obtained by gaussian fitting and deconvolution. The masses were estimated following Hildebrand (1983), using a dust absorption coefficient of $2 \text{ cm}^2 \text{ g}^{-1}$ at 343 GHz (Ossenkopf & Henning 1994), a gas-to-dust ratio of 100 and a temperature of 25 K from SED fitting (Bally et al 2010) for all cores except the hot core A (see section 4), where a range of 25K - 300 K was used.

The continuum emission shows polarization at the level of 0.5 - 15 %, exhibiting the well known polarization hole phenomenon, with the lowest polarization fractions occurring at the highest Stokes I intensities. Assuming that the polarization is due to magnetically aligned dust grains, the derived B field orientations are shown in Fig. 2. The orientation of the polarization shows an ordered pattern, consistent with previous measurements (Cortes & Crutcher, 2006) while reaching a factor of 2 better resolution. It changes significantly over the map and can be decomposed into three regions corresponding to the dust peaks A, B-E and the much weaker C-D. The position angles are approximately perpendicular to each other between A and B-E. The statistics of the position angles are presented in Table 2. The measurements include 50 detections with 3σ or better signal to noise ratio and 17 with 2σ . The intrinsic dispersion of the position angle of the polarization, $\delta\phi$, is calculated by subtracting in quadrature an average position angle measurement error of 7.5 degree, arising from a 5 mJy rms on the Q and U images, from the observed rms of the position angles, σ_{PA} .

For the region B-E, with the most numerous data points, we estimate the strength of the B-field using the Chandrasekhar-Fermi method. Following Crutcher et al (2004),

$$B_{pos} = 9.3 \times n(H_2)^{0.5} \delta V / \delta\phi$$

where B_{pos} , $n(H_2)$, δV and $\delta\phi$ are the plane-of-sky B-field (μG), density (cm^{-3}), FWHM of the turbulent velocity dispersion (kms^{-1}) and the B-field position angle dispersion (degree) respectively. We estimate $n(H_2)$ to be 10^7 cm^{-3} by combining the masses of cores B and E and a size of $5''$. For δV we use a value of 3 kms^{-1} from the single dish HCO^+ measurement of Cortes (2010) with a $20''$ beam, thus avoiding any interferometric spatial filtering. The CH_3CN linewidth, on a much smaller $\sim 1''$ spatial scale, is still similar at 5 kms^{-1} (section 4) and we consider the single dish measurement to be more representative of the velocity dispersion over the $\sim 7''$ region over which the position angle dispersion is measured. The resulting B_{pos} is 6 mG. The mass-to-flux ratio estimated

from these numbers is 3.5, and ~ 1 when a statistical geometric correction is applied, implying a critical to slightly super-critical condition. This is consistent with previous measurements (Cortes & Crutcher 2006; Cortes, 2011) and would suggest that similar conditions are maintained on smaller spatial scales. Nevertheless, we caution that these estimates are subject to large uncertainties.

4. HOT CORE

Strong emission from several hot-core species was detected towards core A. Cores B and C also show emission at much weaker levels. Here, we focus on the remarkable $\text{CH}_3\text{CN}(J=19-18)$ emission from core A, where 11 K-ladder components were detected. The integrated emission and spectrum are shown in figures 1 & 3 respectively. This data set only consists of the compact configuration observations and has a beam size of $2.1'' \times 1''$. The emission is marginally resolved with a source size of $1.5'' \times 0.6''$ ($8000 \times 3000 \text{ AU}$). The detection of a large number of lines from the K-ladder suggests a high temperature, the energy level for the $K = 10$ line being 885 K. The lowest K lines are optically thick, as seen from their being about the same strength. Assuming all the K components are in LTE and trace the same gas, a grid search χ^2 minimization was used to fit for temperature, column density and source size, including optical depth effects (Qiu & Zhang 2009). Using the $K = 2$ to 10 components (fig. 3), we get 300 K, $2 \times 10^{17} \text{ cm}^{-2}$ and $0.6''$ (3000 AU) for the temperature, column density and source size. Fitting only for the optically thin high K components 7-10, the values are 420K, $4 \times 10^{16} \text{ cm}^{-2}$ and $1.2''$. A systemic velocity of 101.5 kms^{-1} was determined and the line width was set at 5 kms^{-1} guided by gaussian fits to the $K = 3, 4$ and 9 components, which appear to be free from blending, and the quality of the fit to the ladder. Such high temperatures are uncommon and only seen in a few other cases, some examples being Orion BN/KL ($\sim 400 \text{ K}$, Wilson et al 1993, Goddi et al 2011) and W51 IRS2 ($\sim 310 \text{ K}$, Mauersberger, Henkel & Wilson, 1987). For comparison, the source size and luminosity can be used to obtain an independent estimate of the temperature. Taking the luminosity from SED fits of $3 \times 10^4 L_{\odot}$ (Bally et al 2010; Herpin et al 2012), following Scoville & Kwan (1976; also Scoville 2012), a dust temperature of 70-120 K (depending on opacity) is obtained for a radial distance of 2500 AU (geometric mean of the semi major and minor axes), assuming heating by stellar radiation. The Herpin et al model also shows a lower temperature ($\sim 150 \text{ K}$; as shown in their fig. 5) for the 2500 AU distance. If this dust temperature also characterizes CH_3CN excitation (Doty et al 2010), its disagreement with the measured temperature of 300-400K points to the possibility that stellar heating alone may not be sufficient to account for the hot CH_3CN . More detailed modeling and corroboration from other data will be needed for further clarity. In summary, we suggest that a high-mass proto-cluster may be forming here within a compact $\sim 0.01 \text{ pc}$ radius region, although we do not yet have evidence for multiplicity.

Table 1: Continuum Emission

ID	RA (J2000.0)	DEC (J2000.0)	Δ RA, Δ DEC "	Peak, Err Jy/bm	Intg. Jy	Maj "	Min "	PA K	Mass M_{\odot}
A	18:47:47.00	-1:54:26.6	0.1 0.1	7.9, 0.61	11.5	1.7	1.3	-52	920 - 80
B	18:47:46.86	-1:54:29.7	0.2 0.2	3.5, 0.52	6.2	2.1	1.9	-63	500
C	18:47:46.41	-1:54:32.9	0.2 0.2	1.9, 0.26	3.7	2.7	1.7	63	300
D	18:47:46.69	-1:54:32.3	0.2 0.2	1.1, 0.15	1.9	2.1	1.5	-69	150
E	18:47:47.05	-1:54:31.0	0.2 0.2	1.2, 0.16	1.6	1.7	0.9	28	130
F	18:47:46.55	-1:54:23.1	0.1 0.2	0.7, 0.08	1.4	3.4	0.9	22	110

all masses estimated using a temperature of 25 K; core A used 25 & 300 K.

Table 2: Polarization and Outflow Position Angles

region	PA_{mean} deg.	σ_{PA} deg.	$\delta\phi$ deg.	Number of pixels
A	-39	14	12	13
B/E	29	17	15	45
C/D	5	8	3	9
All	13	31	30	67
large scale ¹¹	175	± 14		
OF-1	136			
OF-2	135			
OF-3	173			

Dotson et al., 2010

5. OUTFLOWS

The outflows are mapped and studied using CO (3–2) emission. The CO data only consist of sub-compact array observations and thus have a poorer spatial resolution of $5''$. The CO line shows emission to large ($\sim \pm 70 \text{ kms}^{-1}$) velocities. In Fig 2, we present integrated emission over the velocity ranges 60–90 and 120–165 kms^{-1} , with the systemic velocity based on our CH_3CN data being 101.5 kms^{-1} . The CO emission appears to trace three bipolar outflows, two of which are associated with the cores C and F (OF-3 and OF-2 respectively) and the third is centered between core A and B (OF-1). Higher resolution observations will be needed to clarify the location of the driving source for OF-1. Outflows 1 and 2 are oriented the same way but with opposed red and blue lobes. The velocity ranges used were chosen to best delineate the outflows. We estimate outflow masses for the three outflows following the approach in Garden et al (1991). Assuming optically thin emission the outflow masses derived are 12, 11 and 14 M_{\odot} for OF-1,2 and 3 respectively, for an excitation temperature 20 K. Based on the single dish CO(3-2) brightness temperature from Cortes et al (2011), 20 K was taken to be the lower limit and the mass estimate is not very sensitive to temperature, staying within a factor of two for temperatures upto 180 K. The massive outflows imply high-mass star formation. The outflows have time scales of $\sim 10^4$ years, estimated using outflow extents and velocities of $5''$ ($\sim 0.1 \text{ pc}$) and 25 kms^{-1} , pointing to their youth.

6. SUMMARY & DISCUSSION

Our observations show multiple high-mass star formation in the W43-MM1 region. A compact hot core detected in a number of spectral lines has a temperature of ~ 400 K, derived from CH_3CN emission. This high temperature can help in the investigation of high temperature chem-

istry probed by other spectral lines being studied (not included in this letter). Multiple massive outflows were mapped in CO. Dust polarization measurements over the main outflow show an alignment between the outflow and the B-field orientation on the plane of the sky.

We now seek to compare our results with measurements of larger scale B-field reported by Dotson et al (2010). These single dish measurements obtained with the CSO/Hertz have a beam size of $\sim 18''$. While the the position angles for the 6 detections reported are spread over ~ 90 deg, a range similar to our small scale measurements, the inner most four measurements are well ordered, nearly parallel to each other. The outermost two are nearly perpendicular to each other. We exclude the outer two measurements and take the average of the four closest measurements to define the "large scale" field, oriented at a position angle of 85 deg. (175 deg. for polarization) with a range of ± 14 deg. This "large scale" corresponds to $\sim 40''$ ($\sim 1 \text{ pc}$) and the SMA measurements are on a $\sim 7''$ ($\sim 0.1 \text{ pc}$) scale. It is possible to exclude only the most deviant single dish measurement in which case the remaining five measurements trace a gradually changing pattern with the inner most four measurements defining the larger scale field for comparison. As seen in the figure, the field orientation over the main outflow (OF-1) is not parallel to this large scale field measured from the single dish observations. This suggests the possibility that the magnetic fields as seen on the small scales changed orientation from the nearly parallel distribution over the immediate larger scale neighbourhood, either during the formation of the cores or the star formation activity influenced the present morphology.

To assess the possibility of the outflow influencing the B-field morphology, we compare the total mechanical energy in the outflow with energy in the magnetic field, noting that the outflow extent and the region over which the B-field is mapped are comparable. We estimate the outflow

energy to be $\sim 10^{47}$ erg, ($= Mv^2$), taking an outflowing mass M of $10 M_{\odot}$ with a velocity v of 25 km s^{-1} . The magnetic energy calculated is also $\sim 10^{47}$ erg, considering the volume over which the B-field is measured to be a cylinder of length $l = 4 \times 10^4 \text{ AU}$ ($7''$) and diameter $2 \times 10^4 \text{ AU}$ ($4''$), as seen in the map for the B-E region, and a magnetic energy density of $B^2/8\pi = 2 \times 10^{-6} \text{ erg cm}^{-3}$, using the value of B from section 3. As these energies are similar, based on these numbers it is not possible to say if the outflow influenced the orientation of the B-field. Given the uncertainties in these estimates, we would need a large difference to be able to make a more definitive statement. While the comparison is inconclusive, we note that although the outflow mapped in CO traces densities of $\sim 10^3 \text{ cm}^{-3}$ and the B-field is measured by polarization originating in a much denser medium ($\sim 10^7 \text{ cm}^{-3}$), it is still appropriate to compare the energies of the two. This is because, the outflow has cleared a lower density cavity in the dense medium into which it was originally driven and it could have influenced the magnetic field during its early phase. In addition, magnetic tension can couple the magnetic fields in different regions. If alignment is caused by the outflow then the field strength cannot be estimated using the C-F method. However, the estimate in section 5 is still a measure of the upper limit to the B-field, as the position angle dispersion resulting from turbulence is reduced by the outflow induced alignment. Thus, the estimates above are to be only taken as indicative of the strength of the B-field.

There are some studies of alignment between outflows and B-fields in the literature, but the results are inconclu-

sive (see Li et al 2013 for a review and discussion; Curran & Chrysostomou 2007, Wolf et al 2003, Davidson et al 2011, Chapman et al 2013, Hull et al 2013). They are predominantly single dish observations towards low-mass star-forming regions, except the Hull et al. study which used the CARMA interferometer. There is a clear conflict between the results of the most recent Chapman et al. and the Hull et al. studies, the first showing alignment between the B-field and outflow orientations, and the second showing no correlation. As suggested by Chapman et al., (see also Li et al., 2013), the two may be reconciled by the fact that they trace different scales dominated by different processes. Our data correspond to the spatial scales of the Chapman et al study ($\sim 10000 \text{ AU}$) where an alignment is seen, as in our case. However, a simple global picture - a strong magnetic field on large scales directing collapse along its orientation leading to the formation of flattened pseudo-disk structures; rotation axes aligned to the B-field by magnetic breaking and alignment of outflows to this axis - is inconsistent with our observations. This is because (1) the field orientation in our map varies on small scales, and one of the three outflows is not aligned to the other two; (2) the large scale field is not aligned to either of the directions of the outflows or to the small scale B-field. Observations with finer spatial resolutions can help delineate potential pseudo-disk structures and study their rotation and relationship to the outflows and B-field orientations. The presence of multiple outflows within a small region presents a good opportunity to pursue this avenue.

Comments from an anonymous referee which helped improve the paper are gratefully acknowledged.

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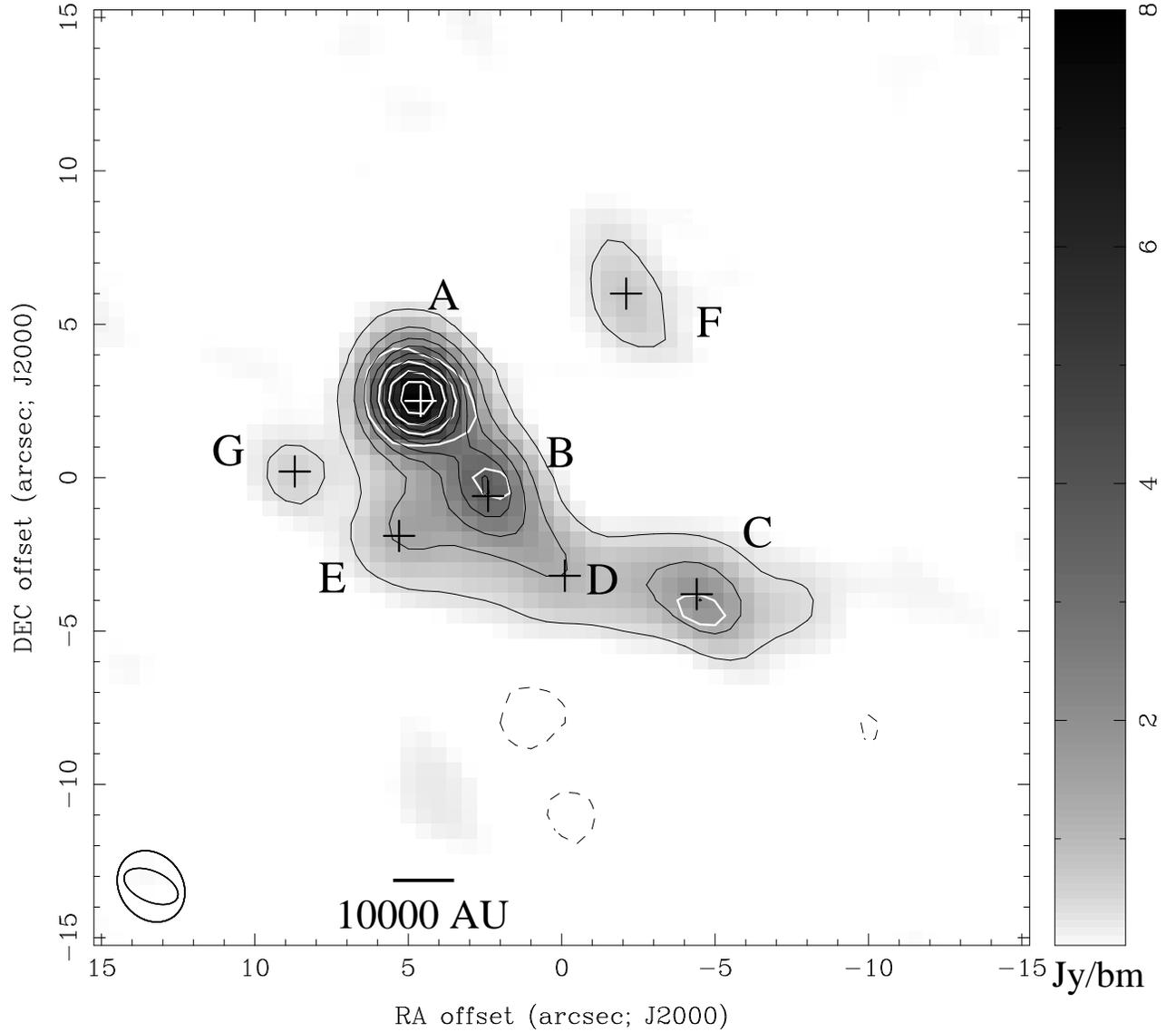


FIG. 1.— The grey scale image and the black contours show the 345 GHz continuum emission. Continuum peaks brighter than the level of the highest negative contour were fitted and labeled A-G (listed in Table 1). The CH₃CN emission integrated over the first four K-components is shown as white contours. The continuum contour levels start at -0.4 Jy/beam with a step size of 0.8 Jy/beam , 1σ being 0.1 Jy/beam . The line contours start at $37.5 \text{ Jy/beam-kms}^{-1}$ with a step size of $75 \text{ Jy/beam-kms}^{-1}$, 1σ being $7 \text{ Jy/beam-kms}^{-1}$. The synthesized beams are shown at the bottom left (smaller beam - CH₃CN).

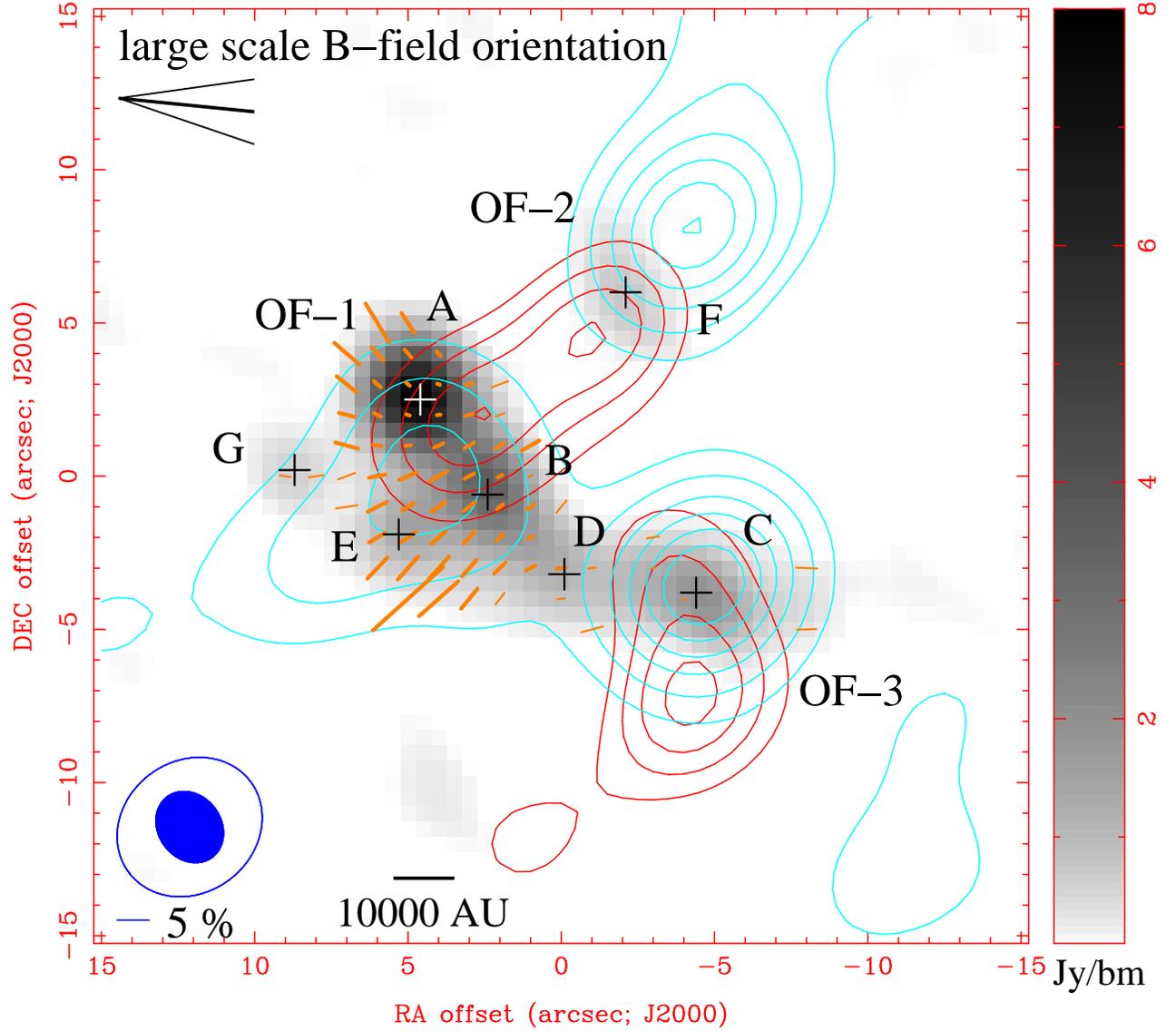


FIG. 2.— Continuum emission, B-field and CO outflows. The CO contours start at $40 \text{ Jy/beam-kms}^{-1}$ and the step size is $40 \text{ Jy/beam-kms}^{-1}$, 1σ being $10 \text{ Jy/beam-kms}^{-1}$. The B-field orientations are shown as line segments with lengths proportional to fractional polarization. Thick and thin segments mark $> 3\sigma$ and $2\sigma\text{-}3\sigma$ measurements, respectively. The orientation of the large scale B-field and its range are also shown. The synthesized beams are shown at the bottom left (filled - continuum). A color version of this figure is available on-line.

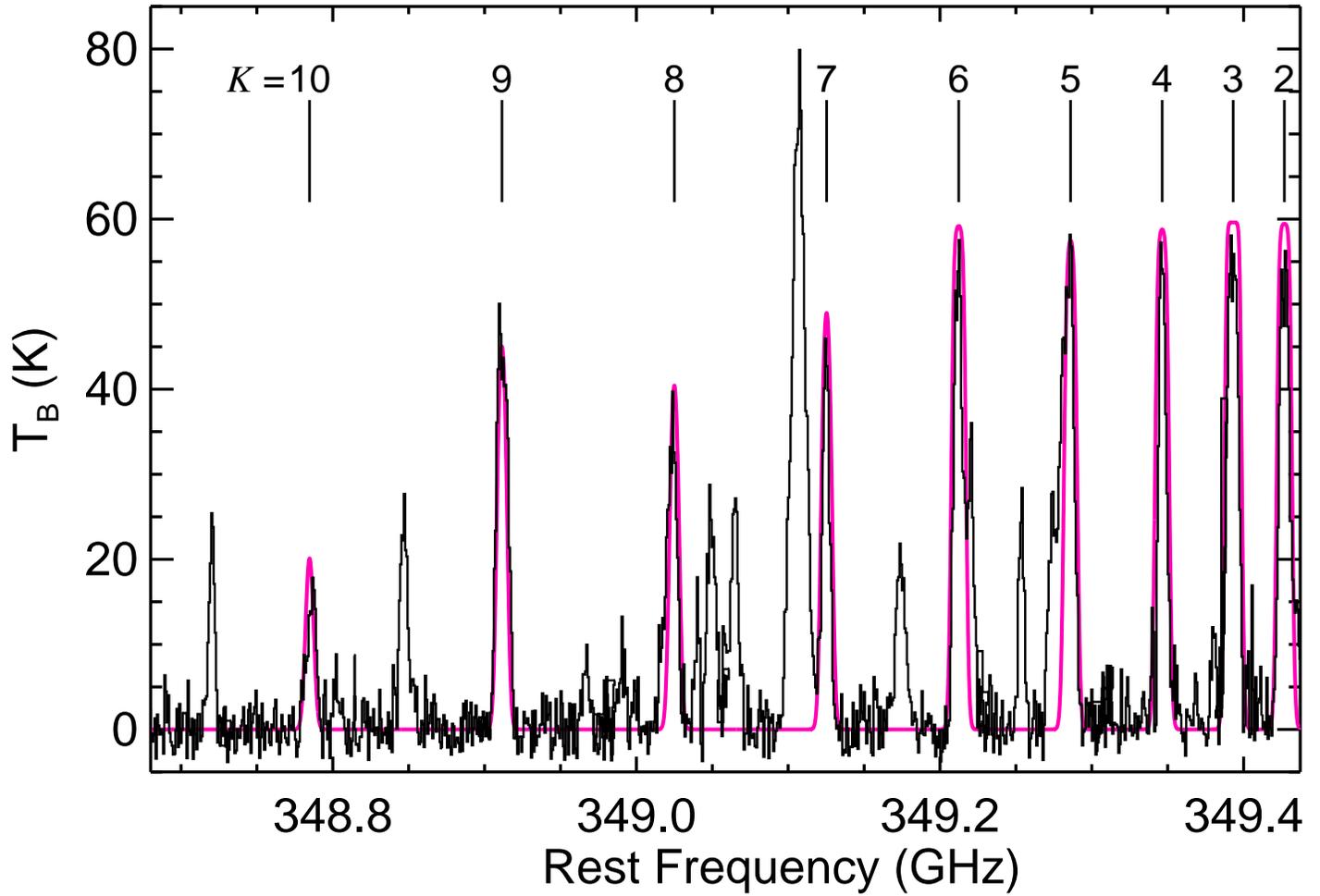


FIG. 3.— Spectrum and fits for the CH₃CN (19-18), K=2 to K=10 lines. The K=0 and 1 components are not shown. The spectrum was extracted over one synthesized beam at the peak. Other prominent lines seen in this spectrum are tentatively identified to be from: CH₃OH (349.107 GHz), CH₂CHCN (348.991 GHz), HCOOCH₃ (349.048 & 349.066 GHz), CH₃¹³CN (349.253 & 349.173 GHz) and C₂H₅OH (348.848 & 348.720).