Extended Molecular Gas in FSC 10214+4724

N.Z. Scoville[1], *M. S. Yun*[1], *R.L. Brown*[2], *and P. A. Vanden Bout*[2]

[1]Owens Valley Radio Observatory, Caltech 105-24, Pasadena, CA 91125

[2]National Radio Astronomy Observatory, 520 Edgemont Rd,

Charlottesville, VA 22903-2475

Received _____

ABSTRACT

We report high resolution imaging of the CO (3–2) emission in the luminous infrared source FSC 10214+4724 at z=2.2853. The maps at resolutions of $2.3\times3.0''$ and 45 km s^{-1} show the CO emission peak coinciding with those of the redshifted Hα and radio continuum. The CO originates from two components: an unresolved core and an extended source ($\sim 1.9\times4.4''$) – elongated southeast-northwest. The implied size is 9×24 kpc for H_0=75 km s^{-1} Mpc^{-1} and q_0=0.5. The extent and morphology of the CO emission is significantly different from that of either the optical or the radio continuum, and it therefore is unlikely that the observed CO fluxes and molecular gas image is affected by gravitational lensing.

The mass of molecular gas implied by the observed CO line flux is $\sim2\times10^{11}M_\odot$. If this mass is spread uniformly over the observed angular extent, the gas must be nearly face-on ($i < 20^\circ$) in order that the derived gas mass does not exceed the dynamical mass. However, a face-on disk is inconsistent with the elongated morphology of the CO which suggests an inclined disk or an interacting galaxy system. We suggest that the "dynamical" mass might be reconciled with the derived gas mass if substantial support for the gas is provided by radiation pressure from the nucleus of FSC 10214+4724. For the observed ratio of infrared luminosity-to-gas-mass ($10^3 L_\odot\ M_\odot^{-1}$), we find that a column density $\leq 2.4\times10^{22} H_2$ cm^{-2} ($A_V \sim 24$) could be supported; this is consistent with the average gas column that is observed. The very high luminosity to mass ratio strongly favors a nonthermal origin for the luminosity since a starburst would require consumption of the entire ISM on a timescale significantly shorter than the dynamical times ($2\times10^7 - 2\times10^8$ years) estimated from the CO data.

Subject Headings: galaxies: individual (FSC 10214+4724) – galaxies: interactions – galaxies: active – ISM: molecules

I. INTRODUCTION

The IRAS galaxy FSC 10214+4724 at z=2.286 has a total luminosity of $\sim 2 \times 10^{14} L_{\odot}$ (H_0=75 km s^{-1} Mpc^{-1}, q_0=0.5), making it one of the most luminous objects yet detected in the Universe (Rowan-Robinson *et al.* 1991). It also has an extraordinarily massive concentration of molecular hydrogen (1-3$\times 10^{11} M_{\odot}$ – Brown & Vanden Bout 1991, Solomon *et al.* 1992a,b). At present the nature of this object and the ultimate source of its luminosity are very uncertain, be it a primeval galaxy undergoing an early ultraluminous starburst or a young dust-embedded quasar. In both scenarios the rich interstellar medium (ISM) can play a pivotal role, feeding a starburst or supplying accretion material to a central AGN. An additional complication in understanding this object is revealed by near infrared imaging which shows a companion source $1.5''$ to the north of the Hα emission peak which could be an intervening galaxy acting as a graviational lens (Matthews *et al.* 1994, Elston *et al* 1994).

In this letter we report high resolution aperture synthesis imaging of the molecular emission in FSC 10214+4724. These observations clearly show the molecular emission to be extended over ~24 kpc. This distribution of emission is very different from the highly concentrated nuclear gas distributions seen in lower redshift ultraluminous infrared galaxies such as Mrk 231 and Arp 220 (cf. Scoville *et al.* 1991), consistent with the notion that FSC 10214+4724 is much earlier in its evolution and is, perhaps undergoing a period of rapid collisional aglomeration and mass accumulation. Our new data enable estimates of the dynamical timescales and masses of the system and, hence, the luminosity-to-mass-ratio with greater certainty than before. These parameters provide constraints on the evolutionary status of the system.

II. OBSERVATIONS

FSC 10214+4724 was observed using the Owens Valley Millimeter Array in three configurations between October 1993 and January 1994. At the time the array consisted of five 10.4 m telescopes, and the longest baseline observed was 200 m E-W. For FSC 10214+4724 for which the systemic redshift is z=2.286, the CO (3–2) transition occurs at 105.2 GHz. The synthesized beams were $2.2\times2.3''$ (uniform weighted) and $2.3\times3.0''$ (natural) at PA$=-87°$. The phase center, central redshift, and adopted angular size and luminosity distances for FSC 10214+4724 are given in Table 1. Each of the telescopes was equiped with an SIS receiver, and measured single sideband system temperatures were typically 250 K in the signal sideband corrected for antenna and atmospheric losses. Spectral resolution was provided by a digital correlator configured with 120×4 MHz channels (11.4 km s^{-1}), covering a total velocity range of 1,300 km s^{-1}. In addition, the continuum emission was measured in a 1 GHz bandwidth analog correlator. The total integration time on source was 37 hours distributed over 6 tracks in the three different telescope configurations. The nearby quasar 0923+392 was used to track the phase and gain variations, and Uranus (T_b=125 K) and 3C345 (4.5 Jy) were observed for absolute flux calibration. The positional accuracy of the resulting maps is $\sim 0.3''$. For 0923+392 the measured flux density was ~4.9 Jy at 105 GHz during the period of the observations. The data were calibrated using the standard Owens Valley array program mma (Scoville *et al.* 1992) and mapped using DIFMAP (Shepherd 1994) and the NRAO AIPS package.

In Figure 1 the vector-average interferometric spectrum on FSC 10214+4724 is shown smoothed to a velocity resolution of 34 km s^{-1}. The spectrum shown here corresponds to the emission spectrum integrated over a $5''$ aperture centered on the phase center (see Table 1) since this spectrum was obtained by averaging only data with fringe spacing $\geq 5''$. The peak flux is 14 ± 2 mJy and the full line width 250 ± 15 km s^{-1}. Both numbers are in good agreement with previous single dish and interferometric spectra (Solomon *et al.* 1992ab, Radford *et al.* 1993).

In Figure 2 maps of the CO emission over velocity ranges with Δv=45 km s^{-1} are shown and in Figure 3 the total integrated CO line flux is shown superposed on the redshifted Hα emission. The cross in the maps indicates the position of the 8 GHz continuum peak which also coincides with the redshifted Hα peak (Lawrence *et al* 1993, Matthews *et al.* 1993). The flux in the integrated map is 4.8 ± 0.7 Jy km s^{-1} and the peak flux in the individual maps for the narrow velocity ranges is 13 ± 2 mJy beam^{-1}. The peak flux corresponds to a beam averaged brightness temperature excess of 0.21 K at λ=2.8 mm or 0.68 K in the rest frame of the source. This corresponds to an absolute brightness temperature of 9.9 K in the rest frame after adding in the cosmic background radiation.

III. Discussion

On the basis of the morphology seen in the channel maps, we decompose the CO emission into two components: an elongated structure, possibly a disk or a galaxy interaction trail, and an unresolved core component. Both are centered on the redshifted Hα peak. For the elongated component, the deconvolved size is 1.9 x 4.4$''$ ($\pm$0.2$''$) at PA=115°, which corresponds to 9$\times$24 kpc. The extented component is approximately outlined by the 4σ (6 mJy beam^{-1}) contour in v=+65 km s^{-1} channel map of Figure 2, and the quoted uncertainty reflects the maximum and minimum sizes inferred from the deconvolution. This feature comprising approximately one-third of the total CO line flux is seen only in the central two velocity maps (v=+20,+65 km s^{-1}). Its full width is Δv $\simeq$ 125 km s^{-1} based on higher spectral resolution channel maps. The observed extent is qualitatively similar but larger than the size inferred by Radford *et al.* (1993). Our new observations with higher frequency resolution should be more sensitive to this narrow velocity feature. The compact core containing two-thirds of the CO line flux appears in six of the channel maps, and the full line width is Δv=228 km s^{-1}. This compact component is spatially unresolved and we adopt an upper limit corresponding to $< 1''$ or a diameter of 5.3 kpc.

The center frequency of the CO(3–2) emission is 105.258 GHz corresponding to a mean redshift of z=2.2853±0.0003. This is significantly different from the mean redshift z=2.2835 for the optical/UV emission lines (Elston *et al.* 1994). A similar offset with higher redshifts for the radio versus optical lines has been noted for lower redshift, high luminosity galaxies (Mirabel & Sanders 1989). It seems likely that the offset observed in FSC 10214+4724 which corresponds to 180 km s^{-1} might be explained if the optical/UV lines originate from gas flowing out of the galaxy, towards us, and the symmetric redshifted emission is extincted by dust within the nucleus.

From the total integrated line flux of 4.8±0.7 Jy km s^{-1}, we obtain a total CO luminosity (both components) of L'_{CO}=5.5×10^{10} K km s^{-1} pc^2, using equation (3) from Solomon *et al.*(1992b). For a conversion factor α=4 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$, the total molecular mass is 2.2×10^{11} $M_\odot$. Apportioning this mass according to the CO emission from the two components, we obtain M_{H_2}=1.5×10^{11} and 0.7×10^{11} $M_\odot$ for the compact core and extended components, respectively. Within the central core, the mass surface density of molecular gas is Σ_{H_2} ≥3.4×10^3 $M_\odot$ pc^{-2}.

Based on the measured sizes and linewidths, it is also possible to estimate dynamical masses associated with the two source components. Using

$$M_{dyn} = \frac{RV_{1/2}^2}{Gsin^2 i}, \tag{1}$$

where $V_{1/2}$ is half of the measured line full width, we obtain 8.0±1.9×10^9 and 1.1±0.3×10^{10} $M_\odot$ for the core and extended components, with no correction for inclination.

The derived estimates for the gas and dynamical masses are clearly inconsistent – the dynamical masses being a factor of 10 lower than the H_2 masses. Two possible resolutions for this inconsistency are that the gas is configured in a nearly face-on ($i \leq 20°$) disk so that the true rotational velocities are three times greater than observed or that the molecular mass has been over-estimated from the CO emission by an order of magnitude. Such face-on geometry has been previously suggested to reconcile the large difference between the

derived H_2 mass and the dynamical mass (e.g. Solomon *et al.* 1992a), but we note that the elongated appearance of the extended component, specifically its >2:1 axis ratio, is in fact more suggestive of a nearly edge-on system (i >66° if it is a thin circular disk). The probability of having the required i <20° is only 7% for randomly oriented disks. We also note that if this is an interacting system, it would be highly unlikely for the gas during the interaction to remain narrowly confined in a plane nearly perpendicular to the line of sight. Nevertheless, we cannot rule out the possibility that the system is nearly face-on since such an orientation might be observationally selected due to the low optical extinction expected. (Although the system was first detected by IRAS in the far infrared, attention would not have been drawn to it if optical spectroscopy had not shown a very large redshift and the CO line had not been bright and narrow and hence more easily detectable.) The discrepancy between the "apparent" dynamical masses and the derived gass masses might also be resolved if the emission regions were elongated along the line of sight. Then the effective radius entering the dynamical mass estimate could be increased; however this preferred geometry seems unlikely although it cannot be ruled out.

A possible over-estimate of the gas mass from the CO emission might arise in two ways: if the observed flux of the CO emission has been artificially enhanced by gravitational lensing, or if the physical conditions within the molecular gas are sufficiently extreme that the CO to H_2 conversion ratio is a factor of 10 lower than the value adopted above. With respect to the possibility of gravitational lensing, we note that Matthews *et al.* (1994) have suggested that the southern arc of emission, seen in deconvolved Hα emission images, might be a gravitationally lensed arc. Recent high resolution HST images by Soifer *et al.* (1995a) support this suggestion. On the other hand, the morphology of the CO and its position angle (115°) are not seen in any other optical/IR (or radio continuum) tracer. Thus, if the molecular gas and the optical emission are both undergoing gravitational focusing, their distributions in the background galaxy must be very different. Lastly, we note that the different morphologies seen in Hα and CO would probably be hard to reproduce in a single

lens system. The Hα morphology consists of the bright spot on the nucleus with a concave arc $1''$ to the south, whereas the CO morphology is a more linear feature, extending diagonally and more extensive than the Hα.

Solomon *et al.* (1992b) discussed the CO excitation and its effects on the conversion ratio, α. Making use of constraints provided by the measured CO line ratios, they find 1.3 $< \alpha <$ 10 for 200 K $>$ T$_{kin}$ $>$ 20 K. The conversion ratio from optically thick CO emission to H_2 mass scales approximately as $n_{H_2}^{1/2}/T_x$. The value of α=4 M$_\odot$ (K km s^{-1} pc^2)$^{-1}$ adopted by us is in the middle of this range, and it is difficult to see how the conversion factor could be reduced by a full order of magnitude in order to bring the derived gas mass in line with the "apparent" dynamical mass. If the metallicity is low as expected for high redshift objects, then the inferred gas mass would be even larger. Lastly, it is worth noting that if the ISM mass estimates are reduced by an order of magnitude to match the inferred dynamical mass, the problem of maintaining the luminosity in this system for a reasonable time become even more severe than they already are.

Under the assumption that the mass derived from the CO emission is in fact approximately correct and that the apparent dynamical mass is an under-estimate of the true mass in the system, we have investigated the possibility that the gas might be supported against self-gravity by pressure forces. Given the high luminosity-to-mass ratio for this system, it is natural to consider the pressure provided by radiation. Under the assumption that the gas is uniformily distributed about a central source of luminosity, it is possible to derive the gas column density at which radiation pressure forces balance the gravitational attraction, assuming that the gas and dust are optically thick and absorb all the radiative momentum. We thus obtain the condition

$$N_{H_2} < \frac{L}{4\pi G c m_{H_2} M} \qquad (2a)$$

$$< 2.4 \times 10^{22} (L/M)_{10^3 L_\odot / M_\odot} \quad cm^{-2}. \qquad (2b)$$

Using the observed far infrared luminosity (L$\sim 2 \times 10^{14}$ L$_\odot$) and the derived molecular mass (2×10^{11} M$_\odot$), we have scaled Equation (2a) to the parameters appropriate to FSC 10214+4724 in Equation (2b). For these parameters, we find that a column of approximately 2.4×10^{22} cm^{-2} of H_2 can be supported, corresponding to $A_V \sim$24 mag for a standard gas-to-dust ratio. This column density is similar to the mean column densities actually inferred for this system, assuming the molecular mass is uniformily spread out over the derived source sizes of the two components. It is also similar to typical column densities of Galactic GMCs; however, if the gas is in fact radiatively supported, the physical structures in which the gas resides are likely to be quite different from the standard GMCs. Elston *et al.* (1994) inferred substantial reddening ($A_V > 5.5$) based on H_α / H_β ratio > 20 (H_β not detected), and the new near IR and optical spectroscopic study by Soifer *et al.* (1995b) also find evidence for heavy extinction. The gas will be Rayleigh-Taylor unstable, probably breaking up into small structures down to the point at which their individual column densities become less than the critical density derived in Equation (2a). When their column densities decrease below this limit, it is anticipated that the material will be lifted back up to larger radii where it accumulates into larger structures with column density exceeding the limit. This gas will then start to rain down once again towards the nucleus. Thus, the material might be continually recycled up and down in a misty halo of the galaxy. In the event that there is significant gravitaional lensing in FSC 10214+4724, these conclusions would still hold provided the infrared luminosity and the CO emission are amplified by the same amount.

In assessing the energy source for the luminosity in FSC 10214+4724, the dynamical timescale provides a strong constraint on realistic models. In scenarios in which the ISM plays an important role, either fueling a massive starburst or in feeding a central AGN, it is reasonable to expect that the time scale for the current high luminosity phase must be at least equal to the dynamical time. From the derived sizes and linewidths in the two molecular

gas components, we can estimate dynamical time scales ($\tau_{DYN} = 2r/\Delta V_{FW}$) of 2.3$\times$ 10^7 and 1.9$\times 10^8$ years for the unresolved and extended components. If the observed luminosity is generated by accretion onto a black hole with an efficiency for conversion of mass into energy of 10%, then the accretion rate must be 140 $M_\odot$ yr^{-1}. If this accretion is to last for at least the dynamical time in the compact component, then the total accreted mass amounts to $3 \times 10^9 M_\odot$ over 2.3×10^7 years. This corresponds to 40% of the apparent dynamical mass in the core component! If instead the luminosity is generated from the formation of high mass stars, as in a starburst, we can estimate the required rate of star formation from simple stellar evolution considerations. For upper main sequence stars, approximately 15% of the original stellar mass is processed through hydrogen burning, while the stars are on the main sequence and for hydrogen fusion, 0.7% of the mass is converted into energy. For these stars, most of their energy output occurs while on the main sequence and thus, we derive a total star formation rate of 1.3$\times$ 10^4 $M_\odot$ yr^{-1} from the observed luminosity (2$\times$ 10^{14} $L_\odot$). Within the dynamical time for the compact core, the implied total star formation rate would be M_*=2.9 $\times$ 10^{11} $M_\odot$ which is 36 times greater than the apparent dynamical mass of the core and similar to the molecular gas content of the entire system. The gas depletion time scale would also be implausibly short ($\sim 10^7$ yrs – also see Elston *et al.* 1994). If the star formation is heavily biased towards upper main sequence stars, a significant fraction of the material going into those stars will be recycled back into the interstellar medium during and at the end of stellar evolution; however, the material cannot be recycled more than $\sim$3 times without the abundances becoming too enriched in processed gas. On the basis of the very extreme total mass which is required under star formation scenarios to account for the luminosity and on the basis of the optical spectra which show no evidence of a starburst component (cf. Elston *et al.* 1994), it seems unlikely that star formation can account for the energetics and optical characteristics of this system.

For very high luminosity-to-mass ratio systems such as FSC 10214+4724 in which the interstellar gas provides a fuel supply for accretion (or starbursts) and in which the gas

may be partially supported by radiation pressure, the activity can be self-regulating as in Eddington-limited accretion. This arises because once the luminosity-to-mass ratio in the system exceeds 100 $L_\odot$ $M_\odot^{-1}$, the accretion of optically thin interstellar gas and dust is prohibited by radiation pressure forces on the dust. (In FSC 10214+4724, the luminosity to mass ratio is ten times higher, and an order of magnitude larger column density can be supported.) In this situation, the only means to maintain the accretion is by lowering the luminosity and hence, reducing the radiation pressure, or by packing the interstellar medium into optically thick clouds with larger column densities. On the other hand, if the central accretion rate increases and the luminosity rises, the minimum column density of clouds which can be accreted will increase to the point at which radial infall will be reduced.

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Figure Captions

Figure 1. Vector averaged spectrum of CO (3–2) emission in FSC 10214+4724 smoothed to 12 MHz (34 km s^{-1}) resolution is shown including all data with interferometer fringe spacing $\geq 5''$.

Figure 2. Maps of the CO emission over 45 km s^{-1} velocity ranges are shown as a function of coordinate offset from 1.4 GHz continnum peak in FSC 10214+4724 (Lawrence *et al.* 1994). The contours are at 4, 6, 8, 10 mJy $beam^{-1}$, and the natural weighted beam is shown. The lowest contour is $\sim 3\sigma$. The velocities are relative to z=2.2853. No significant continuum emission was detected at the level $> 2\sigma$ (3 mJy $beam^{-1}$).

Figure 3. The CO (3–2) emission is shown integrated over all channels containing significant line emission (v=−160 to +200 km s^{-1}). CO emission contours are superposed on redshifted Hα emission (Matthews *et al.* 1994) and the cross indicates the position of the 1.4 GHz continuum peak (Lawrence *et al.* 1994). The contours are spaced by 0.4 Jy km s^{-1} $beam^{-1}$ for the natural weighted beam.

Authors' Addresses

R.L. Brown and P.A. Vanden Bout, National Radio Astronomy Observatory,

520 Edgemont Rd. Charlottesville, VA 22903-2475

N.Z. Scoville and M.S. Yun, Astronomy Department, Caltech 105-24,

Pasadena, CA 91125

Table 1

IRAS FSC 10214+4724

α_{1950}	$10^h21^m31\overset{s}{.}40$	
δ_{1950}	$47°24'23\overset{''}{.}0$	
$< z >_{CO}$	2.2853 ± 0.0003	
Luminosity Distance[a]	11.8 Gpc	
Angular-Size Distance[a]	1.09 Gpc $(1'' \rightarrow 5.29$ kpc)	
Masses	M_{H_2} (10^{10} $M_\odot$)	$M_{DYN}\sin^2 i$ (10^{10} $M_\odot$)
Total	22 ± 3	1.1 ± 0.3
Core	15 ± 2	$< 0.8 \pm 0.2$
Extended	7 ± 1	1.1 ± 0.3

Notes to Table 1:

a) $H_o = 75$ km s^{-1} Mpc^{-1}, $q_o = 0.5$

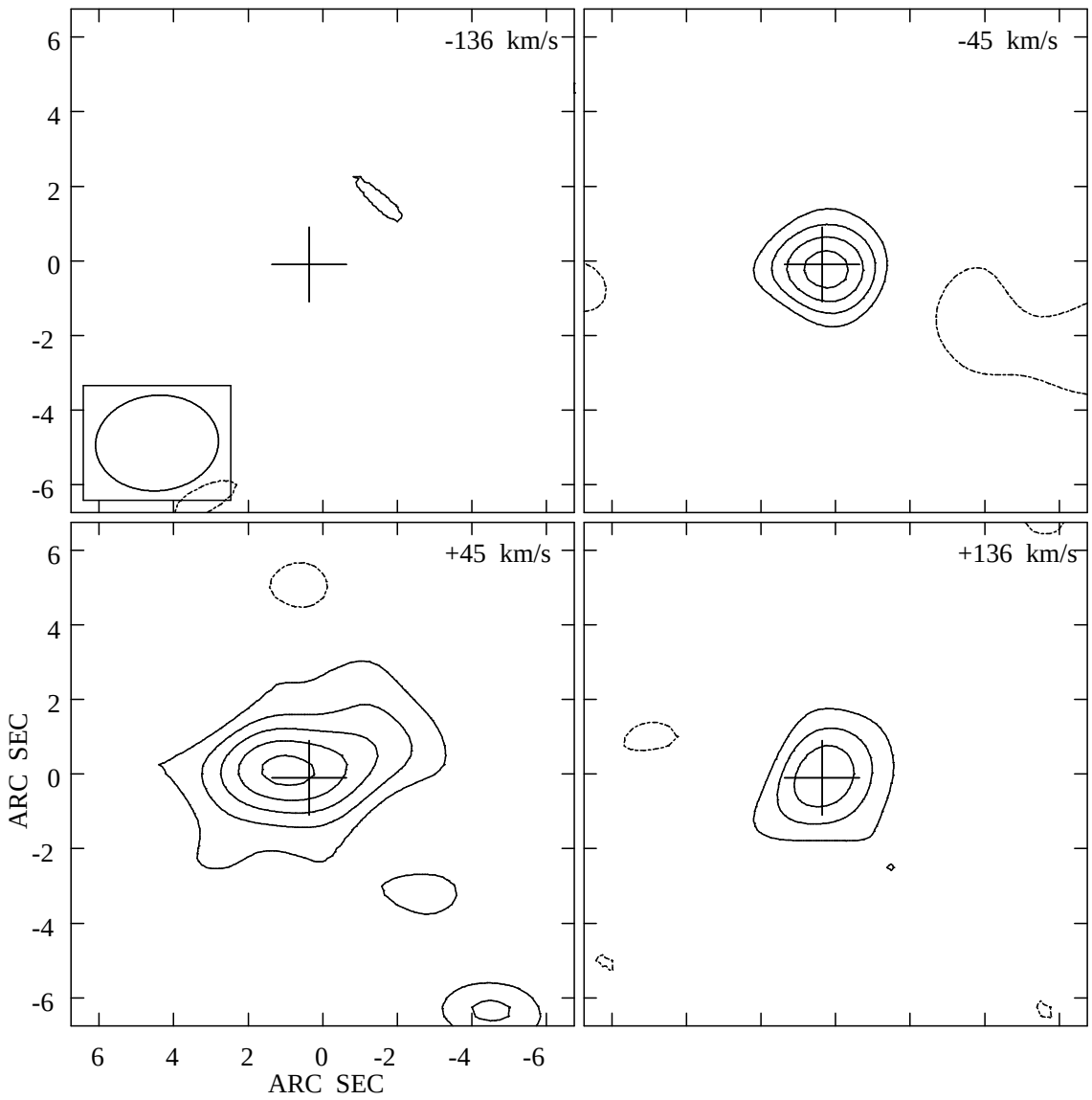

Figure 2. Channel maps.